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INVESTMENT PLANNING OF INTERDEPENDENT WATERWAY IMPROVEMENT PROJECTS

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Advisory Committee:

- Associate Professor Paul Schonfeld, Chairman/Advisor
- Professor Everett Carter
- Professor Larry Bodin
- Professor Thomas Corsi
- Assistant Professor Gang-Len Chang

INVESTMENT PLANNING OF INTERDEPENDENT WATERWAY IMPROVEMENT PROJECTS

by

David Roy Martinelli

Department of Civil Engineering
University of Maryland
College Park, Maryland

for

Navigation Division
U.S. Army Corps of Engineers
Water Resources Support Center
Institute for Water Resources
Casey Building
Ft. Belvoir, VA 22060-45586

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EXECUTIVE SUMMARY

Investment planning for reconstruction and rehabilitation of inland waterway lock and dam facilities may be classified as capital budgeting. Capital budgeting is typically associated with large investments of resources over long periods of time while subject to a budget constraint. Capital budgeting situations arise in the public sector when an overall constraint is imposed on the size of the budget so that it is not possible to implement all projects having positive net benefits. While there are perhaps 60 or more lock and dam improvement projects believed to be economically viable, it is clear that their combined costs exceed available funds so that some delays in start times are unavoidable.

Project evaluation, sequencing, and scheduling are the three primary phases of capital budgeting. Project *evaluation* involves the assessment of benefits and costs, *sequencing* is establishing the implementation priorities among projects, and *scheduling* is assigning the start times for the projects. Current methods of capital budgeting are quite satisfactory for analyzing mutually exclusive projects and reasonably satisfactory for independent projects. However, there is an obvious void in analyzing projects that are interdependent. This is because the three phases of capital budgeting must be performed simultaneously for interdependent projects. For mutually exclusive or independent projects, the evaluation phase may be performed independently of sequencing and scheduling.

The benefits (or cost reductions) associated with navigational lock improvements are interdependent, i.e. the improvement benefits of a given lock are affected by the acceptance or rejection of other lock improvement projects. The interdependencies at locks are with respect to delays. More specifically, the arrivals at a given lock can be "metered" due to the delays at previous locks. If a system of two or more locks are interdependent, then the total delay of the system will be somewhat less than the sum of the isolated delays. The interdependence in a system of locks may therefore be measured by the ratio of system to isolated delay, S/I.

The coefficient S/I is a component of a cost function that consists of delay and capital costs associated with a system of locks. A functional expression (or metamodel) for S/I was developed through an experiment involving a microsimulation model for waterway traffic. The experiment employed distance, critical utilization and relative utilization of locks as factor variables and four levels of each factor were considered. The functional expression for

S/I was expanded to include systems of more than two locks. A numerical example of the cost functions involving four locks revealed that interdependence may significantly decrease the present value of system costs.

The functions developed make it possible for the system costs associated with a given project implementation combination to be expressed functionally. In other words, a system cost may be computed for any given implementation combination at any given point in time. The system cost curve associated with given implementation combinations may therefore be plotted versus time. By superimposing system cost curves for various implementation combinations, a minimum cost expansion path may be identified through the lower "envelope" of curves. The expansion path defines both the sequence and schedule of projects. The values of the system costs at any point along the expansion path represent the evaluation phase of capital budgeting. Therefore, all three phases of capital budgeting are performed simultaneously while moving along the expansion path. However, the number of possible expansion paths is combinatorially large.

To identify the optimal or near optimal expansion path, a search heuristic was employed. The heuristic begins with an initial implementation sequence based upon an independent evaluation of projects. Beginning with the null alternative, projects are considered for implementation in the order of the current ranking. As each implementation decision is made, a swap is considered between the highest and second highest ranked projects. The decision to swap is based on computing the cumulative cost over relevant regions. This may be easily performed visually if the curves are expressed graphically. An electronic spreadsheet template was developed to implement this methodology for actual proposed improvements on various segments of the inland waterway system. Preliminary data were used to exercise the methodology on the lower Ohio River segment as an illustration.

A mathematical programming model was introduced as a conventional formulation for capital budgeting of interdependent projects. This formulation was shown to have some shortcomings. First, numerous integer decision variables are required, which exceed the practical limits of integer programming. Second, it is necessary to estimate an excessive number of interaction coefficients between projects over a range of possible start times. Third, interdependencies are considered only among the projects that are implemented. An alternative formulation that addresses these shortcomings has been developed and shown to

be effective for the application to inland waterway lock improvements.

In the alternative formulation, the evaluation and sequencing are performed simultaneously, i.e. the development of application-specific evaluation functions is separable from the sequencing and scheduling. This allows us to take advantage of improvements in the evaluation model without altering the method. The method is computationally and conceptually straightforward to apply, and has been shown to adequately reproduce simulated results for two and three lock systems. The sequencing algorithm was shown to yield promising results based on an experiment involving systems of four and six locks.

The method does employ analytic assumptions, some more valid than others. The systems considered in the formulation must have a series geometric orientation. In reality, the inland navigation network has junction locks which cannot be included in the existing methodology. However, the number of junction points is relatively small for the inland waterway network. Also, the framework of the method allows for the future inclusion of a model that captures interdependencies involving junction locks.

A second assumption is that locks are interdependent only with respect to delays. While locks may be interdependent with respect to other factors, these factors are likely to be incorporated in the delay. For example, locks may be interdependent with respect to tow characteristics. However, average tow size is considered when estimating the capacity of locks and is thus incorporated in delay. Also, a significantly large portion of rehabilitation benefits are associated with the reduction in tow delays.

A third assumption is that a one-directional analysis is sufficient for obtaining values for the total delay of a system of locks. While the simulation experiment was performed for two directional systems, the expansion of the results assumed one directional traffic. The validation of the analytic coupling technique showed that for three lock systems, the total delay of the system may be predicted with sufficient accuracy. However, it is likely that accuracy is lost in the portion of delay that exists at each lock due to the one-directional assumption.

Numerical uses of the resulting method have revealed that interdependence may significantly reduce the present value of system costs. In other words, the net present value or benefit cost ratio (BCR) of interdependent lock improvements will be less than if they were independent.

This effect will tend to postpone the time when a capacity expansion is justified. Thus start times were indeed higher for interdependent projects.

Because delay interdependencies and system costs may now be expressed functionally, it may be possible to analytically prove some of the numerical observations of this dissertation. An example would be an analytic proof that the sequence of projects is not greatly affected by the presence of interdependencies. Such a proof could lead to criteria for other interdependent applications.

A second topic of future investigation is the development of a simulation or analytic model for determining the interdependence at junction locks. This would help in applying the method to applications with more complex network structures.

A third extension to this dissertation would be to develop enhancements to the project sequencing heuristic that would improve the likelihood of yielding the optimal solution. In Section 5.8 one such extension was discussed. This particular extension involved considering project swaps beyond the first unsuccessful swap. Currently, the algorithm advances to the next iteration upon the first unsuccessful swap.

CHAPTER 1
INTRODUCTION

The Capital Budgeting Process

Capital budgeting is the process of determining which investments or "projects" will be funded and pursued in order to meet prespecified goals and objectives over a planning horizon. A set of projects to be implemented constitute a capital investment program. The term capital budgeting is sometimes used interchangeably with priority programming, program planning, capital investment analysis, and others. To assist planners in funding decisions, capital budgeting models have been proposed for use in evaluation based on various quantitative criteria. Techniques such as present worth economics, risk analysis, "what if" financial models, and mathematical programming have all been employed in capital budgeting.

There are many decisions that may be thought of as investments, and hence incorporated into the capital budgeting process. Investment decisions may include facility replacement, major rehabilitation and maintenance, financing options and others [Clark 84]. There are two properties that characterize a decision as capital budgeting: 1) the assets normally represent relatively large commitments of resources, and 2) the funds remain invested for long periods of time. In the context of transportation planning (and many other fields), the complete capital budgeting process may be divided into three components: project evaluation, project selection, and project scheduling. These budgeting phases are almost always assumed to be independent of each other and therefore, are performed sequentially. However, because the objective function remains the same throughout the process, two or more of these phases may, at least conceptually, be performed simultaneously. Depending on the application, certain phases of the process may be combined or omitted. Each of these three phases is described below.

The *project evaluation* phase involves quantitatively assessing the benefits and costs of each project under consideration for each period of the planning horizon. The benefit and cost estimates for each project are then combined to formulate a measure of effectiveness, usually net present value, internal rate of return, or benefit-cost ratio.

The *project selection/sequencing* phase uses measures of effectiveness (MOEs), agency or firm priorities, budget, and other factors to determine the relative priority of

projects. If there are no constraints, then sequencing, or ranking, is made simply according to the relative measures of effectiveness. However, under budget or other constraints, some "desirable" projects may not be implemented or priority ranking may be different from a ranking according to highest value of the MOE. Typically, when constraints are introduced, a new MOE that incorporates the constraints is defined.

Assuming a project sequence has been established, *project scheduling* involves assigning a start time to each project. While this phase is conceptually simple, budgets and other constraints may impose delays on when projects are permitted to start.

Applying the capital budgeting process to planning provides insight into 1) the relative priority of projects, 2) the quantification of total program benefits and costs and 3) the start times and funding profiles for each project. Associated with each phase of the process are various methods and assumptions that are commonly employed. In the sections that follow, merits and limitations of some of the more popular techniques and assumptions in capital budgeting are discussed.

Project Evaluation

Because project benefits and costs are accrued over a planning horizon, it is helpful to use cash flow models to represent investments. In dealing with a series of cash flows, each sum may be treated separately in determining its equivalence. Using the decomposition and superposition properties of cash flows, the combined effects of all sums on the final result may be obtained. In a cash flow stream, the estimated benefits in a given period, B_t, are denoted as positive cash flows, while costs, C_t, are denoted as negative. The net cash flow in a given period, A_t, is the difference between the benefits and costs. In project evaluation, the most common measure of relative benefits and costs is the sum of the discounted net cash flows or net present value, NPV. The NPV is given by

$$NPV = \sum_{t=0}^{T} A_t(1+r)^{-t} \qquad \text{Eq. 1.1}$$

where r_t, is the is the minimum attractive rate of return or MARR[1] for private projects or the social rate of discount for public projects, and T is the planning horizon. If the discounted benefits exceed the discounted costs, i.e. if NPV > 0, then the project is regarded as desirable.

A second common measure of project evaluation is the ratio of discounted benefits to discounted costs or benefit-cost ratio, BCR. The BCR is given by

$$BCR = \frac{PVB}{PVC} \qquad \text{Eq. 1.2}$$

where PVB and PVC are the discounted benefits and discounted costs respectively. Clearly, if BCR > 1, then NPV > 0 and the project is considered desirable. Either the NPV or the BCR may be used as measures of project acceptability.

To evaluate the economic merits of a capital investment program (a set of scheduled projects), an expression must be formulated by which benefits and costs of individual projects may be combined to represent the economic merits of the overall program. A standard expression is simply the sum of the NPVs of all projects to be implemented or total net present value, TNPV. The TNPV is therefore given by

$$TNPV = \sum_{i=1}^{P} NPV_i = \sum_{i=1}^{P} PVB_i - \sum_{i=1}^{P} PVC_i \qquad \text{Eq. 1.3}$$

It is important to note that the TNPV expression is computed through a linear addition of the benefits and costs of all projects. This process explicitly assumes that the projects are independent of each other with respect to their benefits and costs. Actually, projects may be economically independent or interdependent. Independence among projects necessarily implies that 1) neither a project's benefits nor costs will be affected favorably or adversely by the acceptance or rejection of any other project(s) and 2) it must be technically feasible to implement the project regardless of the acceptance of other project(s). Often, projects will not be totally independent, but will have some level of interdependence. For example, a proposed tunnel at

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[1]MARR = max {(1) cost of borrowed money, (2) average cost of capital, (3) opportunity cost of capital}

a given site may be economically dependent on proposed access roads, since without the access roads, the benefits of the tunnel may not be realized.

It is clear that interdependencies between projects may lead to a TNPV that is either greater or smaller than that estimated by the linear Equation 1.3. If the acceptance of interdependent projects yields a greater TNPV, then the projects may be regarded as complementary. Complementary relationships may or may not be mutual. Consider a light rail line and a parking garage for a stop on the line. While the garage would deliver little or no benefit without the light rail line, the reverse is not true. In the extreme case, one or more complementary projects may be prerequisites. In other words, in the case of two projects, project B may be technically impossible or would result in no benefits without project A.

Unlike complementary projects, if the acceptance of interdependent projects yields a lower TNPV than Equation 1.3, then the projects could be considered substitutes to some degree. Two projects that serve nearly the same purpose are likely to be substitutes. An example of two substitute projects would be an express bus and light rail line connecting the same corridors. In the extreme case, substitute projects are mutually exclusive; that is the benefit expected from either proposed project will be completely eliminated by the acceptance of the other or it is technically infeasible to implement both projects.

The possible project relations may be conceptually modeled as a dependency spectrum from mutually exclusive at one extreme to prerequisite at the other. Figure 1 shows that in moving from the left to the right of the spectrum, there is an increasing degree of complementarity. Similarly, in moving from the right to the left, the degree of substitutability increases. The center of the spectrum represents the independent relationship.

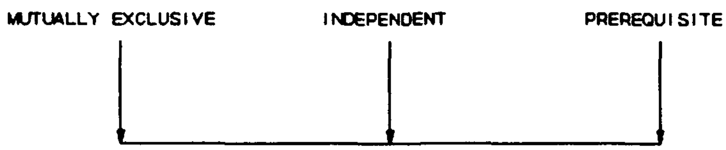

Figure 1 - Spectrum of Possible Project Relationships

The standard analysis techniques for capital investment projects do not deal with the interdependencies among available projects. For this reason, it is common practice to reduce all problems to either independent or mutually exclusive sets of projects. This is usually done by amalgamating those projects with strong interdependencies and ignoring any remaining interdependencies. The extent to which this practice leads to good decisions has been obscured by the lack of analysis techniques capable of adequately representing interdependencies in specific instances.

Project Selection/Sequencing

Explicitly, the project selection process chooses a subset of n investment projects from a set of N desirable projects in the most desirable order. The problem confronting the decision analyst is to choose from among the X possible permutations of project sets the one which yields the maximum return, Eq. 1.4. At this stage in the process, the MOE chosen to represent project "return", or "payoff" is of no significance to the analysis.

$$X = \sum_{k=0}^{N} \binom{N}{k} = 2^N \qquad \text{Eq. 1.4}$$

One possible method of selecting a set of projects might be to choose the highest payoff set out of a complete enumeration of sets that satisfy the budget and other constraints. However, as a practical matter, complete enumeration becomes infeasible as a method of finding optimal combinations of projects as the number of projects becomes large. The number of possible combinations to be examined is 2^N if there are N projects available. Thus, if there were 30 total projects, enumeration would involve examining about 1.07×10^9 alternative project sets.

If determining the optimal sequence of projects is to be considered as part of the project selection process, then the number of programs to be examined is even greater. In the project selection problem, the number of possible project sets is equal to the sum (over the number of possible set sizes) of statistical *combinations*, while the sequencing problem must seek the *permutation* from among n! permutations representing possible project sequences. If one is to consider, by complete enumeration, all of the possible sequences of 30 projects, then about 2.6×10^{32} alternative programs must be examined. Clearly, it becomes prohibitively expensive to select and/or sequence projects through complete enumeration of alternatives.

When projects are independent and only a budget constraint is present, a common approach is to rank all desirable projects according to benefit-cost ratios. By ranking the projects, the problem of too many combinations is eliminated. However the method is not exact in all cases. If the budget constraint is exactly reached after a number of projects have been selected according to descending BCRs, then the subset of projects selected is optimal, i.e. produces the maximum TNPV [Bierman 75]. However, if the budget constraint is not exactly reached but will be exceeded by the inclusion of the next ranking project, then it is not necessarily true that the group of projects under the budget constraint is the best selection. In general, if a relatively large number of independent projects of approximately the same size can be selected under a budget constraint, it is likely that this selection strategy leads to an optimal or near optimal result.

Figure 2 schematically shows a case where the BCR ranking scheme is likely to lead to the best selection, even though the actual investment is slightly under the budget constraint. The budget constraint is represented as a vertical line at the maximum allowable cumulative expenditure. Because a project with a BCR < 1 is not desirable, a second constraint on the minimum allowable BCR, as represented by the horizontal line, is necessary.

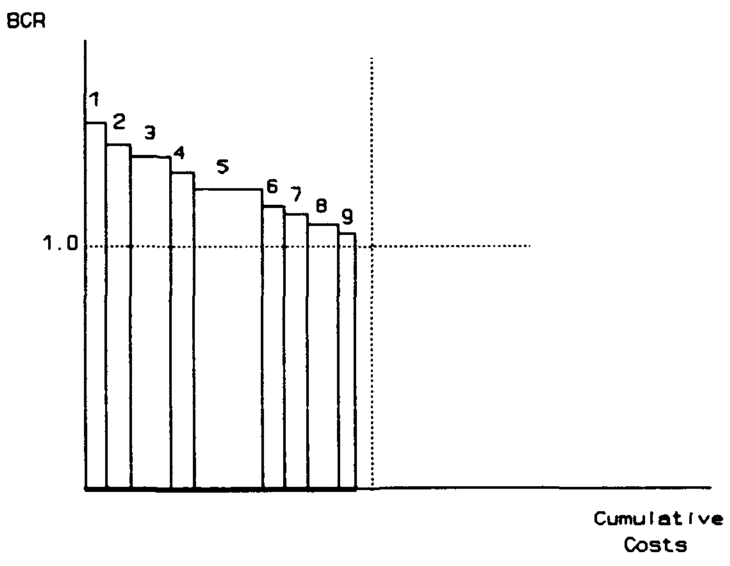

Figure 2 - BCR Ranking Scheme

When project interdependencies exist, the performance measure, e.g. BCR, cannot be determined until a project portfolio has been selected; therefore, combinations cannot be eliminated according to a ranking scheme. Some popular analytic techniques for solving the project selection problem include mathematical, integer, and dynamic programming, branch and bound algorithms, and heuristics. In Chapter 2, an assessment of the literature will provide some insight into the advantages as well as the limitations of these methods.

The Inland Navigation System

System Description

Inland waterways, as shown in Figure 3, are an important part of the nation's transportation network. Approximately 16 percent of the intercity freight in the U.S. moves by waterway. As shown in Table 1, coal, petroleum products, and grains are the top three tonnage commodities, accounting for about 60 percent of the inland waterway commerce. The National Waterways Study (NWS) forecasts an increase in total U.S. waterborne traffic from 1,915 million tons in 1977 to a 2,890 million tons by 2003 [USACE 87].

The system consists of 11,000 miles of shallow draft channels (18 feet or less) and another 1000 miles of deep draft channels. There are over 200 lock and dam sites and thousands of structures throughout the system. Locks and dams are essential for creating stepped navigational pools with reliable depths for navigation. However, if not maintained, these facilities can become major constraints to inland navigation. In raising and lowering vessels from one navigation pool to the next, locks require time to service vessels; if this time increases due to malfunctioning lock components or traffic levels approach capacity, severe queues may develop in busy channels, leading to costly delays.

Waterway capability or capacity is defined as the maximum tonnage that the waterway can pass per year. The capability of a waterway system to serve traffic can be measured by several performance indicators which apply to individual lock and dam sites as well as the overall waterway system. However, locks generally determine the maximum traffic volume or capacity of the waterway.

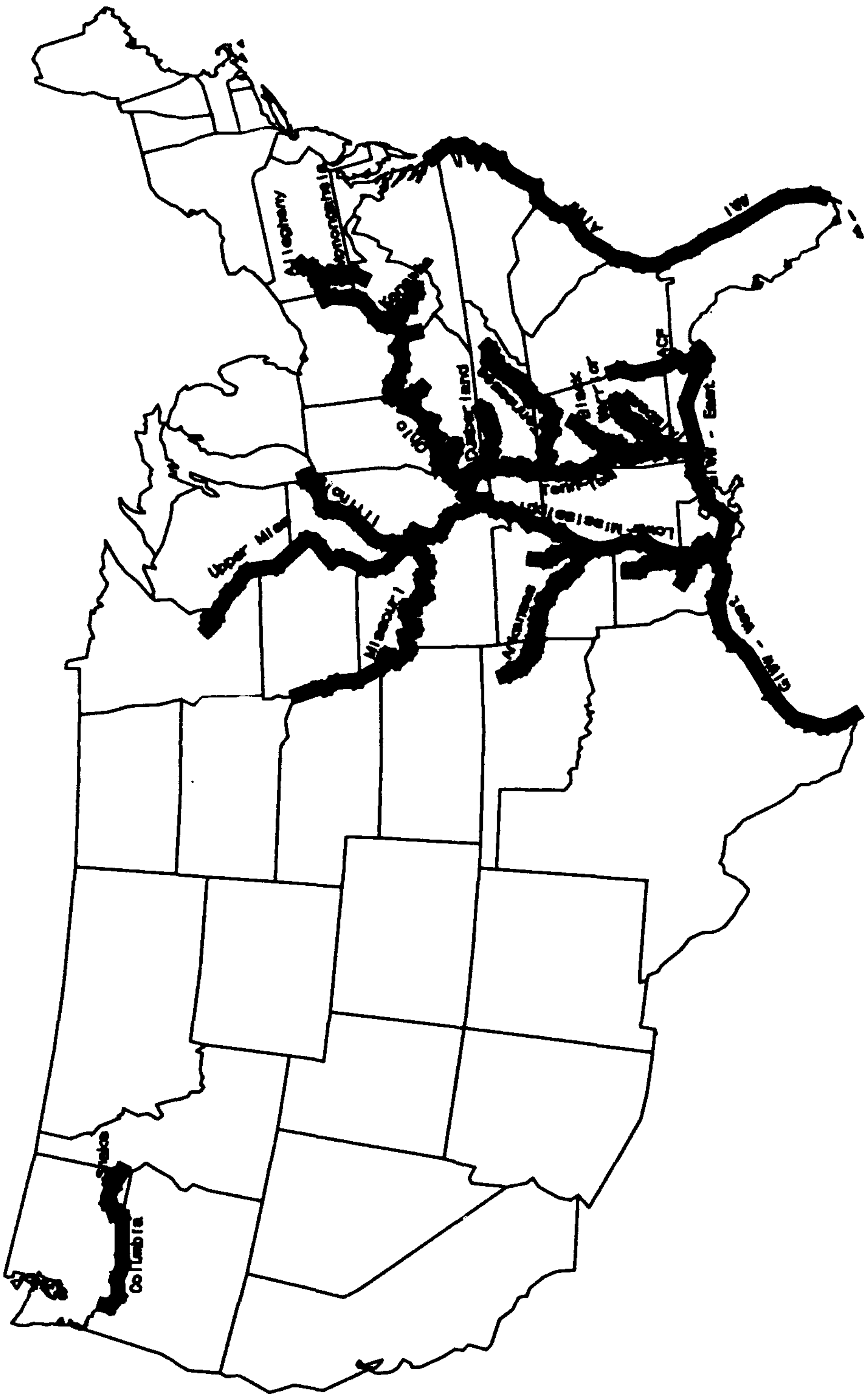

Figure 3 - The Inland Waterways System

Table 1 - MAJOR COMMODITIES USING INLAND WATERWAYS

Rank	Commodity	Millions of Tons	Percent of Total
1	Coal	131.6	24.6
2	Petroleum Products	101.5	19.0
3	Selected Grains	59.1	11.0
4	Crude Petroleum	41.6	7.8
5	All other	201.2	37.6

The National Waterways Study identified a need for substantial investment in the waterway infrastructure. This need stems from 1) waterway traffic projections that approach or exceed the capacity of some existing facilities and 2) the age and physical deterioration of facilities. Currently there are about 100 locks that have exceeded their 50 year design life [USACE 87]. Experience with aging locks indicates that lock closures or stalls and subsequent navigational delays can be expected to increase as locks age. Also, aging locks tend to have substantially longer tow processing times. Stalls and high processing times can result in increased shipping costs, delayed shipments, loss of cargo, higher logistics costs, and other adverse effects.

In response to a declining waterway infrastructure, the Inland Waterways Trust Fund (IWTF) was authorized by the Inland Waterways Revenue Act of 1978 and amended by the Water Resources Development act of 1986. These laws established the IWTF user fees (10 cents per gallon of fuel before 1990, increasing to 20 cents in 1995), for barges operating on 27 waterways, and authorized appropriations from the fund. According to the law, the fund will be available "*for making construction and rehabilitation expenditures for navigation on the inland and coastal waterways...*". Historically, the primary means of affecting such improvement has been to replace chambers, increase chamber size, or add a second chamber in parallel to an existing one.

There are several benefits associated with reconstruction and rehabilitation of navigation facilities along the inland waterways. The Water Resources Council manual identifies four types of navigation benefits:

1. cost reduction benefit (same origin-destination; same mode):

   a. reductions in costs incurred from trip delays;

b. reductions in costs because larger or longer tows can use the waterway (e.g. by channel straightening or widening);

c. reduction in costs by permitting barges to be fully loaded (e.g. by channel deepening);

2. shift of mode benefit (same origin-destination; different mode);

3. shift of origin-destination benefit; and

4. new movement benefit.

By far the most significant of these benefits is the reduction in trip delays associated with expanded capacity resulting from reconstruction. However, the delays at a given lock may depend significantly on conditions at various other locks. Therefore, the benefits of reconstructing locks are likely to be interdependent.

Problem Description

Capital rationing situations arise in the public sector when an overall constraint is imposed on the size of the budget so that it is not possible to immediately implement all projects having an excess of benefits over costs. Such is the case with inland navigation lock and dam reconstruction projects. While there are perhaps 60 or more improvement projects believed to be economically viable, it is clear that their combined costs exceed available funds so that some delays in start times are unavoidable.

The Inland Waterways Trust Fund (IWTF) is a critical source of funding for the proposed lock and dam reconstruction projects. The IWTF consists of fuel taxes (ranging from $.10 per gallon before 1990 to $.20 after 1994) for tows operating on 27 waterways. The IWTF coupled with a Federal matching share define the budget constraint for a capital budgeting problem for lock improvement projects. There approximately 60 projects believed to be economically justifiable. Many of these projects are expected to have delay interdependencies are expected. A comprehensive and reliable capital budgeting approach must incorporate these interdependencies.

This research considers the scope and methodologies for more system-based capital budgeting of inland waterway improvement projects, i.e. the evaluation, selection, and scheduling of a subset of investment alternatives. Current methods of capital budgeting are quite satisfactory for

analyzing mutually exclusive projects and reasonably satisfactory for independent projects. However, there is an obvious void in analyzing projects that are interdependent. Interdependencies exist whenever the benefits and costs of any one project may depend on the acceptance of one or more other projects. It seems that overcoming this void requires 1) the development of a framework whereby application-specific evaluation functions may be formulated for aggregating benefits and costs among interdependent projects, 2) the development of a technique whereby the numerous permutations of possible programs may be represented and searched, and 3) the determination of efficient project implementation schedules.

Problem Statement

The problem addressed herein is to develop a methodology for solving the capital budgeting problem among interdependent lock replacement or expansion projects. The procedure should be one that is not overly restrictive in the number of projects that may be considered and may be readily understood and employed by practicing engineers and planners. The product of this research is likely to be 1) a validated framework for computing the total net benefits of a combination of interdependent lock improvement projects and 2) an algorithm or step-by-step procedure for searching the solution space formed by the possible permutations of interdependent waterway projects.

Document Overview

Chapter 2 examines the areas of the literature that have addressed the issues of representing project interdependencies and project selection and sequencing, given interdependence. The review identifies some of the major difficulties and research needs in this area of capital budgeting.

Chapter 3 outlines the methodology for obtaining an aggregate evaluation of interdependent waterway improvement projects and discusses the methodology for addressing the excessive number of program permutations that must be evaluated in order to select the group and sequence of projects that maximize discounted total net benefits. While some optimization algorithms have been developed for the selection/sequencing problem, they significantly limit the number of projects considered. The context of the solution methods developed are be transportation planning. There are numerous problems in transportation for which a generalized budgeting methodology would be appropriate. These include

capacity expansion programs for highways, bridges, airports, waterways, etc.

Chapter 4 presents the analysis conducted in developing programmable functions to compute the total system costs (TSC) for a set of interdependent lock improvement projects.

Chapter 5 presents the analysis for using the evaluation functions in selecting the permutation of interdependent projects that minimizes the TSC. A case study for a segment of the inland waterway navigation system is provided.

CHAPTER 2
REVIEW OF RELEVANT LITERATURE

Capital budgeting problems are of interest in several diverse disciplines. Civil and industrial engineers, economists, operations research analysts, and finance specialists all address some aspects of the capital budgeting problem. Each field has a unique perspective and priorities, utilizing different sets of tools and techniques. The budgeting literature has grown in each field, but has tended to diverge from, rather than converge to, a unified perspective. However, with some exceptions, there tend to be two characteristic approaches: the engineering and management science approach, and the economics-finance approach. Engineers and management scientists are concerned with normative models for decision making and techniques for their solution (e.g. mathematical programming and simulation). On the other hand, economists and financial analysts are concerned with developing general criteria and rules (e.g. capital asset pricing models and portfolio theory).

One could further classify the approaches by noting that the engineering-management science approach is concerned with the selection of *sets* of projects under certain assumptions while the economics-finance approach is concerned with *single* projects. Mutually exclusive, prerequisite, complementary, and substitute projects are significant concerns of the former, while the appropriate discount rate or the rate of return that projects must clear are concerns of the latter. While financing approaches have led to significant contributions in capital budgeting, this literature review shall consider only the engineering-management science approaches.

Representing Project Interdependencies

The existing literature on interdependencies among capital projects is sparse, at best, compared to the literature on other aspects of capital budgeting. Most engineering economics, finance, and capital budgeting texts only briefly mention the interdependence problem. The first, and most cited work in this area is that of [Weingartner 66]. Weingartner began with the classical Lorie-Savage capital budgeting problem [Lorie 55] and reviewed linear, integer, quadratic, and dynamic programming approaches to address some special cases of project interdependence. However, these cases only include mutually exclusive projects and several derivatives of prerequisite projects, which are only special cases of interdependence.

When the number of budget constraints is small, the Lorie-Savage formulation may be viewed as a special case of the knapsack problem. The Lorie-Savage formulation is given by Equations 2.1 - 2.3.

$$\max \text{TNPV} = \sum_{i=1}^{N} NPV_i \; y_i \qquad \text{Eq. 2.1}$$

$$\text{s.t.} \quad \sum_{i=1}^{N} C_{it} \; y_i \leq B_t \qquad t=1...T \qquad \text{Eq. 2.2}$$

$$y_i \in (0,1) \qquad i=1...N \qquad \text{Eq. 2.3}$$

Where NPV_i is the net present value, C_{it} is the cost of project i in period t, and B_t is the budget limit in period t. The decision variable y_i is 1 if project i is included in the budget and 0 otherwise. Weingartner added the following constraint to allow for mutually exclusive projects:

$$\sum_{i \in M} y_i \leq 1 \qquad \text{Eq. 2.4}$$

where M is the subset of projects that are mutually exclusive. If project j is a prerequisite for project k, then the following constraint is required:

$$y_j \leq y_k \qquad \text{Eq. 2.5}$$

This formulation comes obviously short of representing the spectrum of possible dependency relationships diagramed in Figure 1. Nemhauser and Ullmann [69] used dynamic programming to solve a program with the following extension to Weingartner's objective function and budget constraints

$$\max \text{TNPV} = \sum_{i=1}^{N} NPV_i \; y_i + \sum_{i=1}^{N-1} \sum_{j=j+1}^{N} d_{ij} \; y_i \; y_j \qquad \text{Eq. 2.6}$$

$$\text{s.t.} \quad \sum_{i=1}^{N} PVC_i \; y_i + \sum_{i=1}^{N-1} \sum_{j=j+1}^{N} V_{ij} \; y_i \; y_j \leq B_t \quad t=1...T \qquad \text{Eq .2.7}$$

In the above formulation, d_{ij} represents the deviation (positive or negative) from linear addition in the return from two interacting projects i and j. In other words, the return from implementing both i and j is $NPV_i + NPV_j + d_{ij}$. Similarly, the variable V_{ij} in the budget constraints represents the deviation (positive or negative) from linear addition in cost from projects i and j.

However, only pairwise interactions are represented by the above formulation. This simplification allows the projects to be conceptually represented by an undirected graph in which the projects are vertices (1,2,...,P) with an edge connecting those projects that are interrelated. In general, the graph will not be connected, i.e. there will be clusters of projects with each cluster corresponding to a set of projects that interact with each other but do not interact with any other. The existence of clusters in such a graph could reveal the extent to which the problem may be decomposed. Decomposition is an effective technique in reducing problems of great complexity.

A shortfall of this formulation, however, is that only pairwise interactions are represented. Depending on the application, three, four, or more projects may be simultaneously dependent. Extensions to include these "third-order", "fourth-order", etc. dependencies are discussed in [Gear 80, Fox 84, Janson 88] and others. Their formulation for the three-project case is:

$$\max TNPV = NPV_1\, y_1 + NPV_2\, y_2 + NPV_3\, y_3 + NPV_{12}\, y_{12} + NPV_{13}\, y_1\, y_3 + NPV_{23}\, y_2\, y_3 + NPV_{123}\, y_1\, y_2\, y_3 \qquad \text{Eq. 2.8}$$

Note that if all three projects are selected then the TNPV = $NPV_1 + NPV_2 + NPV_3 + NPV_{12} + NPV_{13} + NPV_{23} + NPV_{123}$. Clearly, there are difficulties inherent with this approach, specifically, all possible interactions among projects must be assessed. The assessment of these interactions would be extremely difficult, if not impossible, particularly those of higher order. Even if it were possible to assess the parameters in Equation 2.8, it would require evaluating an interaction term for all possible project combinations, an unwelcome exercise.

One way to simplify the assessment of interaction parameter values is their classification. For example, in the literature of research and development (R & D) project evaluation, efforts have been made to obtain a standard classification of project interactions. Interactions have been classified by R & D planners as either internal or external. Internal interactions are those involve the

attributes of the projects themselves, while external interactions arise from overall social and economic changes which have effects that cut across many, if not all subsets of the project set.

Several authors including [Schoeman 68, Aaker 78, Baker 75, Gear 80, Fox 84] have adopted the following three categories for internal interactions 1) cost or resource interaction, 2) benefit, payoff, or effect interaction, and 3) outcome probability or technical interaction. Further classifications exist within each of these categories. As expected, cost (benefit) interactions occur when the total cost (benefit) of a set of projects does not equal that of the sum of the individual projects. Outcome interactions among projects occur if the probability of success of a given project depends on the outcome of one or more other projects.

Fox and others [Fox 84] utilized classification to propose a framework whereby interaction parameters are determined implicitly rather than explicitly as in Equation 2.8. Instead, the model requires that a profit function for producing and selling M products $\pi(\mathbf{W}_t)$, and its vector of parameters $\mathbf{W}_t$ be assessed, together with the impacts of projects on the values of the parameters. The following example profit function is given

$$\pi(\mathbf{W}_t) = \pi(\mathbf{m}_t, \mathbf{q}_t, \mathbf{k}_t) = \sum_{j=1}^{M} [m_{jt} q_{jt} - k_{jt}] \qquad \text{Eq. 2.9}$$

where the parameters m_{jt}, q_{jt}, and k_{jt} are the unit contribution margin, unit sales, and fixed costs respectively, associated with product j in period t. In a mathematical programming formulation, Equation 2.8 is replaced with a generalized expression for the expected present value of selected projects $GPV(y_1, y_2, \ldots, y_N)$ (y_i and N as previously defined). Note that one form of the GPV function is Equation 2.8 and a special case of the GPV is the additive model as given in Eq. 2.1. Assuming no cost or impact interactions, and given a profit function and a vector of project success probabilities α, yields the following expression for GPV

$$GPV = E\left[\sum_{t=0}^{T} (1+r)^{-t} \left[\pi(\mathbf{W}_t + \sum_{i=1}^{N} \Delta W_{it}\ \alpha_i\ y_i - \pi(\mathbf{W}_t)\right]\right] \sum_{i=1}^{N} PVC_i y \qquad \text{Eq. 2.10}$$

where r is the discount rate and T is the number of periods in the planning horizon.

The authors show that if the profit function is assumed to be linear in its parameters, then Eq. 2.11 reduces to Eq.

42.1. However, in general, the profit function is not linear, and it has been shown by example that the effects of interactions can be quite significant [Bonini 75]. The model is shown to reduce to a binary quadratic integer program with N binary variables, N continuous variables, and 4N + 1 constraints. A similar framework in a more general context is presented in [Srinivasan 87].

Selection and Sequencing Interdependent Projects

Project Selection

There have been several efforts to review and summarize the state-of-the-art in project selection techniques. While several reviews [Cetron 67, Gear 71, Angood 73, Naslund 73] fail to mention project interdependence, others [Meadows 68, Baker 74, Baker 75] explicitly note that a major limitation of existing models is their failure to include interdependencies. Baker and Freeland concluded that among the most important limitations of existing approaches is the "*inadequate treatment of project interrelationships with respect to both value contribution and resource utilization* [Baker 75]."

The project selection problem has been formulated and solved through integer programming techniques by several authors [Weingartner 66, Cochran 71, Taha 75, Johnson 85, Clark 84]. However, as discussed in the introduction, selection problems involving interdependent projects quite often will exceed the capabilities of existing integer programming packages. This is because the measure of effectiveness for any interdependent project cannot be determined until the project set has been specified.

A second project selection technique discussed in the literature is dynamic programming, first applied by Weingartner [66] and further developed by others [Nemhauser 69, Morin 71,74]. A dynamic programming formulation of the project selection problem is based on recursively obtaining the optimal return from the set of projects included. Let $f_k(c_1,\ldots,c_T) = f(\mathbf{C})$ be the optimal return at the kth iteration (or state), where c_t is the available budget in period t at state k. For a set of N possible projects, it is necessary to obtain $f_N(\mathbf{B})$, where $\mathbf{B}$ is the vector of budget limitations. If $\mathbf{E}_p = (e_{1p},\ldots,e_{Tp})$ is the vector of capital expenditures required for project p over time, then the equations for obtaining $f_N(\mathbf{B})$ recursively are:

$$f_0(C) = 0 \qquad \text{Eq. 2.11}$$

$$f_{p+1}(C) = \max\,[f_p(C),\ NPV_{p+1} + f_p(C - E_{k+1})] \qquad \text{Eq. 2.12}$$

where Equation 2.12 applies for $p = 1,\ldots,n-1$, and $f_k(C - E_{k+1}) = -\infty$ if any component of $C - E_{k+1}$ is negative. This formulation may be expanded to include binary interactions between projects such as those expressed in Equation 2.8. However, most dynamic programming algorithms inherently must limit the number of interactions to 2N [Nemhauser 69].

Project Sequencing

A problem similar in many respects to the general project sequencing problem, for which some literature exists, is the capacity expansion problem. The basic capacity expansion problem consists of determining the sizes of facilities to be added so that the present value of costs of all expansions is minimized. Capacity expansion models have been developed for various public programs in which substantial capital investments are needed. A special class of capacity expansion is concerned with sequencing a set of available expansion projects according to a minimum demand. Each project is defined by its construction cost and capacity. Given the pattern of demand over time, the problem is to select the sequence of projects that should be implemented to satisfy the demand at any point in time while minimizing the total discounted costs.

Figure 4 gives a graphical depiction of the project sequencing problem for capacity expansion. The vertical axis has units of capacity while time is plotted on the horizontal. At time 0, demand is assumed to be either 0 or fully satisfied, while an expansion project is introduced the moment demand equals capacity. This procedure forms a step function for available capacity with each jump corresponding to the implementation of a capacity expansion project.

There are some differences worth noting between the general project sequencing problem for capital budgeting and project sequencing for capacity expansion. First, in capital budgeting, the primary constraint is the budget, while in capacity expansion the primary constraint is the minimum capacity. Second, project sequencing is constrained by an upper bound on the budget in the former while being constrained by a lower bound on demand in the latter.

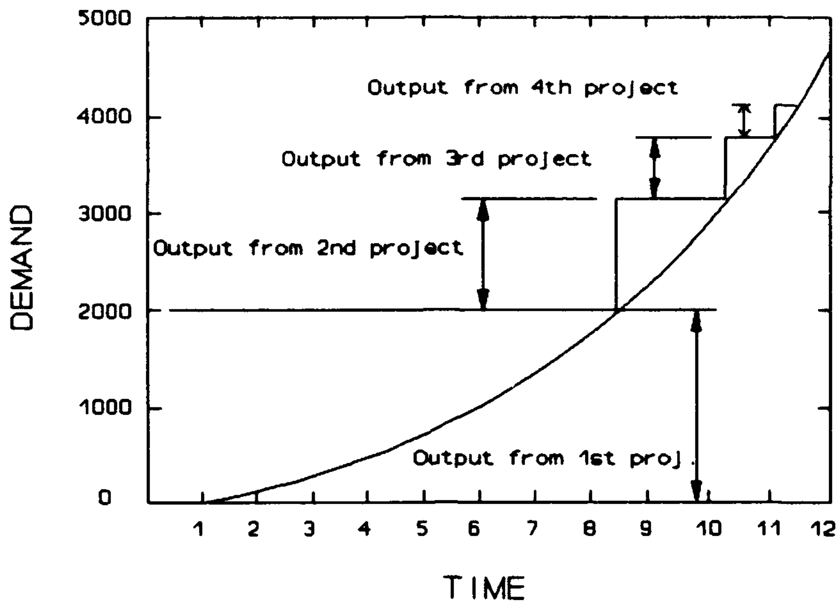

Figure 4 Sequence ^f Expansion Projects to Meet Demand

Despite these differences, they both share the same inherent combinatorial difficulties, that is in both cases it is prohibitively expensive to evaluate all possible combinations. Also, it is likely that the problems are mutually transformable for independent projects.

Erlenkotter [73a] and others [Butcher 69, Morin 71, Morin 73] have proposed dynamic programming formulations to solve capacity expansion project sequencing. The number of possible states in their formulations grows exponentially with the number of available projects, thereby limiting N to about 20. It has been shown by Erlenkotter [73a] that for linear demand, if given the optimal *selection*, then the optimal project *sequence* can be obtained without dynamic programming. This is because, for linear demand functions, the equivalent cost rate for each project is shown not to depend on the implementation time.

Early dynamic programming models for sequencing capacity expansion projects may be adapted to accommodate some simple project interactions. This has typically been done by replacing constants for capacity or costs with functions of the state vector. For example, a dynamic programming model was formulated by Erlenkotter [73b] for interdependent hydroelectric projects. In this model, the capacity provided by a set of k projects is $Q(Y_k)$, where

$\mathbf{Y}_k=(y_1,\ldots,y_k)$ and y_i is 1 if project i is included and 0 otherwise. It is assumed that total capacity is nondecreasing as individual projects are added. While interactions do not allow the total capacity to be determined by summing the individual project capacities, the total capacity for any specified *set* of projects may be determined. Also, let $C_{k+1}(\mathbf{Y})$ be the total investment cost associated with adding the next project, and D(t) be the nondecreasing demand projection.

The assumption is then made that expansion of capacity will never be optimal before existing capacity is completely used by demand growth. This assumption is not reasonable for certain applications. For example, for waterway locks, the costs of delay begin to increase quite rapidly before the capacity is reached. Therefore the time, $\tau(Q)$, at which an expansion will be required from capacity level Q is:

$$\tau(Q) = \sup\,[t \mid D(t) \leq Q] \qquad \text{Eq. 2.13}$$

To establish a recursive dynamic programming relationship, the function PVC($\mathbf{Y}$) is defined as the optimal discounted costs for all expansions to be undertaken subsequent to those already included in $\mathbf{Y}$. With r as a discount rate, PVC($\mathbf{Y}$) is determined recursively by:

$$PVC(\mathbf{Y}) = \min_{i \notin Y}[C_i(\mathbf{Y})\ e^{-r\tau(Y)+C(Y\cup i)}] \qquad \text{Eq. 2.14}$$

While most authors have employed mathematical programming techniques to the sequencing problem, heuristic approaches to capacity expansion project selection have been introduced by Butcher et. al. [69], Erlenkotter [70], Morin [70,71,72], Mitten-Tsou [72], Tsou-Mitten [73], Zipkin [80] and others. Most employ project ranking schemes guided by rules which apply weights to the objective function and constraints. If a problem can be shown to have numerous near-optimal solutions, then the potential effectiveness of heuristic approaches is quite high. The authors cite several potential advantages of heuristics over "brute force" optimization, the most obvious being the reduced computational effort required for realistically large problems. Also, the rules used to rank and select projects, and methods used to weight the constraints are relatively transparent in comparison to more complex mathematical programming algorithms.

Tsou and Mitten [73] introduced a project selection heuristic for water resource expansion. While the context of the authors' discussion is independent projects, the procedure might be applied to some projects involving interdependencies. Beginning with zero projects, each step

of the procedure adds the one project with the lowest R-index, $R_i(Q)$

$$R_i(Q) = \frac{PVC_i}{1-(1+I)^{\tau(Q)-\tau(Q+O)}} \qquad \text{Eq. 2.15}$$

where PVC_i and O_i are the present value of costs and output (units of capacity) for project i, respectively and r is the rate of discount. As in the Erlenkotter model, the function $\tau(Q)$ is the inverse demand function. The index given in Equation 2.16 is derived from an expression for discounted costs. The technique starts with the computation of the R-index for each project i with Q=0, and the project with the lowest index is selected as the first project. This procedure is repeated with the remaining projects with Q equal to the cumulative output of all selected projects.

Morin [74] examined the optimality of this heuristic and showed that it is guaranteed to yield the optimal sequence if the following conditions are satisfied: 1) the demand is equal to 0 at time zero, equal to the total output at time T, and always increasing, and 2) the sequences based on the R-indices are invariant over all possible cumulative outputs Q. These conditions are always satisfied by a linear demand. Morin also pointed out that the heuristic is not likely to be near optimal when there is a positive demand at time zero which exceeds the capacities of two or more or the largest projects.

Summary

There is a recognized void in the capital budgeting literature in techniques to represent project interdependencies and to search through the extensive number of implementation possibilities. By far the most utilized tools for addressing these issues have been integer and dynamic programming. However, several authors have experienced some success in applying heuristic solutions to independent projects.

While there have been several variations of mathematical programming formulations and solution procedures for capital budgeting of interdependent projects, two inherent problems remain unresolved. The first is that assessing third, fourth and higher order project interactions is extremely difficult, if not impossible. In addition, the very nature of the current methods tend to incorrectly imply that such interactions are exceptions to the usual case of independence. The second inherent difficulty is that problems involving 20 or more projects

result in a combinatorial explosion of program possibilities and tend to far exceed the capacities of the most common analytic techniques.

CHAPTER 3
METHODOLOGY

In this chapter, the methodology for evaluating, selecting, sequencing, and scheduling interdependent lock improvement projects is explained. In developing this methodology, an emphasis has been placed on separating the project evaluation and sequencing steps. This allows improved evaluation measures to be later used with the sequencing technique.

The nature of project interdependencies is different for given applications. For example, characterization of the interdependence among prospective manufacturing technologies is relatively unrelated to that of prospective transportation facilities. For this reason, the evaluation phase of capital budgeting should be somewhat application-specific. On the other hand, a methodology for the project selection and scheduling phase may be more general. In this chapter, a conventional formulation of the capital budgeting problem is presented and criticized before the proposed method is prescibed. The latter overcomes some shortcomings of the conventional formulation and exploits some properties of the inland navigation system.

Conventional Formulation

The problem may be formulated as a 0-1 integer programming problem where the objective is to maximize the total net present value (TNPV) subject to a budget constraint for each period. The decision variables y_{is} indicate the projects to be implemented and their appropriate start dates.

$$\max \quad TNPV = \sum_{i=1}^{N} \sum_{s=1}^{T} \left[NPV_{is}\, y_{is} + \sum_{j \neq i} \sum_{s=1}^{T} \sum_{v=1}^{T} d_{ijsv}\, y_{is}\, y_{jv} \right] \qquad \text{Eq. 3.1}$$

$$\text{s.t.} \quad \sum_{i=1}^{N} \sum_{s=1}^{T} C_{ist}\, y_{is} + D_t - D_{t-1}(1+I) = B_t \qquad t=1..T \qquad \text{Eq. 3.2}$$

$$y_{is} \in (0,1) \qquad s=1...T,\ i=1...N \qquad \text{Eq. 3.3}$$

$$\sum_{s=1}^{T} y_{is} \leq 1 \qquad i=1...N \qquad \text{Eq. 3.4}$$

$$D_0 = 0 \qquad \text{Eq. 3.5}$$

$$D_t \geq 0 \qquad t=1...T \qquad \text{Eq. 3.6}$$

In the above formulation, NPV is the net present value of project i with start time s, while d_{ijsv} represents the deviation (in present dollars) from linear addition in the net return from two interacting projects i and j with start times s and v, respectively. This deviation may be more explicitly stated as difference between the deviation in benefits and the deviation in costs

$$d_{ijsv} = b_{ijsv} - c_{ijsv} \qquad \text{Eq. 3.7}$$

where b_{ijsv} and c_{ijsv} are the is the deviation in present value of benefits and costs, respectively, for two interacting projects.

In the formulation, C_{ist} is the required expenditure in period t, for project i, starting in period s, D_t is the unspent budget in period t, I is the interest rate, and B_t is the limit on expenditures in period t. N is the total number of all projects considered, while T is the number of time periods in the planning horizon. The variable D_t is included to allow unspent portions of the budget in each period to be "rolled over" into the budgets of succeeding periods. The decision variable y is 1 if project i is to start in period s, and 0 otherwise

There are significant shortcomings with this formulation. First, only paired interactions are represented; depending on the application, three, four, or more projects may be simultaneously dependent. Second, the number of integer variables is excessive. For example, a problem with 30 projects and a planning horizon of 50 years (time periods) could have 1,500 binary integer (y_{is}) decision variables. This same problem would also require approximately 2.25 million interaction coefficients (d_{ijsv}'s) as well as 75,000 cost parameters (C_{ist}'s). While many problems may be smaller than this example, most mixed-integer programming packages have serious difficulties with problems of this size. Also, interdependencies are only considered to exist among those projects that are actually implemented.

There is a need to formulate the problem in a manner that is not as computationally expensive and does not require excessive estimation of interaction parameters. The separation of the application-specific evaluation phase from the more general sequencing and scheduling phases is the first step in obtaining such a formulation.

Methodology for Interdependent Project Evaluation

Because project interdependencies may be application-specific, it is helpful to first identify the basic source of the interdependence. For navigational lock improvements, project construction costs are assumed independent, but projects are interdependent with respect to delays. That is, the total delays incurred at one lock are in some way related to the delays at one or more other locks. Although it is assumed that lock rehabilitation projects are interdependent only with respect to delay costs, this may be done without changing the nature of the problem nor compromising the applicability of the basic methodology to similar problems. The assumption of independent construction costs is reasonable, given the capital intensive nature of the project costs.

In the conventional formulation, the d_{ijsv}'s represent an assessment of the interdependency between pairs of projects i and j. In capital budgeting, assessment of each dependency term is necessary only to the extent that the *aggregate effect* of all terms cannot be computed. Therefore, if the aggregate effects of interdependencies can be determined directly, then for capital budgeting purposes, assessing the individual dependency terms is not necessary. For example, if a micro-simulation model for lock system operations can determine the total delay (and therefore lock rehabilitation benefits) for a system of interdependent locks, then the model can be used to *directly* determine the TNPV of a combination of interdependent projects. Given this property, an alternative objective function of the problem may be stated.

$$\max \text{TNPV} = f(y_{is}) = f(\mathbf{Y}) - C_i \qquad i=1,\ldots,N \quad s=1,\ldots,T \qquad \text{Eq. 3.8}$$

where $\mathbf{Y}$ is an NxT matrix of y_{is}'s, and C_i is the capital cost of project i. The function $f(\mathbf{Y})$ may be a simulation, analytic, or empirical model that aggregates the interdependent costs and benefits of a set of projects. Even if an analytical function $f(\mathbf{Y})$ exists, it is likely to be complex. Also, any mathematical programming formulation with decision variables y_{is} will be difficult to solve given the large number of binary integer variables and the limited capabilities of current integer programming packages.

An equivalent cost minimization objective function may be written by considering the costs associated with delays rather than the benefits associated with a change in delays. The total cost to be minimized, therefore, has a capital component and a delay component.

$$\min TPVC = C_{is}\, y_{is} + g(y_{is}) = C_{is}\, \mathbf{Y} + g(\mathbf{Y}) \qquad \text{Eq. 3.9}$$

where TPVC is the total present value of costs. The term $g(\mathbf{Y})$ is a function whereby the total interdependent delay for a system of locks may be computed for all possible combinations of project implementations. Therefore, the evaluation stage of capital budgeting corresponds to establishing a $g(\mathbf{Y})$ evaluation function which computes the delay costs of a set of interdependent projects for the inland lock application.

Network Representation

As with other transportation modes, the inland waterway system can be modeled as a network. The network representation for the waterways has been utilized to analyze numerous problems associated with navigation planning e.g. commodity and traffic projections, traffic assignment, and inventory policy. Typically, the linehaul segment of the waterway system is represented by network links and the lock and dam facilities by nodes. However the reverse is also possible. Nodes may also be used to represent the various origins and destinations. The network conceptually carries flows of commodities, vessels, or other quantities. Figure 5 shows a network diagram of a typical waterway segment. The locks in this diagram each have one main chamber servicing tows in both the upstream and downstream directions.

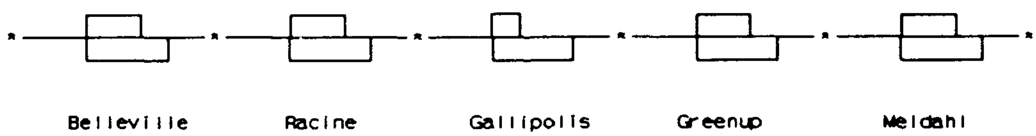

Figure 5 Network Representation of Waterway Segment

There are several advantages of a network representation of waterway segments, the most significant being the variety of quantitative tools available for analysis. The link and node representation is highly compatible with the data structures of most computer programming languages, therefore better allowing for the development of simulation and other models. Queuing theory, also is quite adaptable to a network representation of the system.

There are some useful network properties worth noting that exist for waterway segments that do not exist for most

other transportation modes. The first of these properties is that of the network geometry, which for all practical purposes, may be considered fixed. For example, adding links to a highway network, is at least technically feasible in most cases, while adding a link to the waterway network would be a tremendous undertaking. Second, the connectivity of the network is relatively low compared to other modes. Network *connectivity* is the extent to which nodes are mutually connected. In the case of the air transportation mode, many origin nodes may be directly linked to many destination nodes. However, even the most critical junction nodes along the waterway have an incidence (number of penetrating links) of only three. Third, and somewhat related to the second, is the tree structure of nearly the entire inland waterway network. A network may be called a tree if it contains no cycles; therefore the number of links is always one less than the number of nodes.

Special properties of the waterway network may be exploited in establishing the relationships among candidate facilities. For example, the low connectivity of the waterway network indicates that there may be several places where the total network may be decomposed into smaller networks. Decomposition is an effective technique for solving combinatorially large problems. Also, it is realistic to model many of the locks as a series of elements, rather than some more complex network geometry.

Defining Lock Improvement Interdependencies

Because a majority of the project benefits may be derived from reduced delays associated with improved capacity, project interdependencies will be derived from the correlation of delays among locks. If locks are independent, then no matter how a lock operates, it does not affect the performance of any other locks upstream or downstream. Then the total delay of a system of locks is no different than the sum of the delays of each lock acting in isolation.

If interdependencies between two or more locks in a system exist, then the total delay of the system will be different from the sum of the isolated delays. If the total system delay S is equal to the total isolated delays I then the locks may be considered independent. Therefore, a ratio of system delay to isolated delay, S/I may serve as a measure of the total interdependence in the system. If S/I =1.0, then there are no interdependence effects and if S/I < 1.0 then interdependence effects exist. It may be noted that S/I cannot exceed 1.0. It should also be noted that we are concerned with assessing the *total effects* of

interdependence and not an itemization of all component interdependencies.

It is possible to establish a theoretical lower bound for S/I. Consider a one directional system of two identical locks A and B. Also, assume that the system is deterministic, i.e. the spacing between vessels is unchanged when traveling between Locks A and B and the service times are not a random variable. Although there may be delays, W_A at Lock A, there will not be any delays at Lock B due to a metering effect from Lock A. In other words, tows will arrive at Lock B with a spacing that exactly corresponds with the service times at B. However, if each lock is considered in isolation, then the delays at B will equal the delays at A yielding a total delay of $2W_A$ for the two lock system. Therefore the lower bound on S/I for a two lock system is 1/2. In general, for similar deterministic systems of more than two locks

$$S/I = 1/n \qquad \text{Eq. 3.10}$$

which represents a lower bound on S/I (or an upper bound on the amount of interdependence in the system). For the more realistic stochastic case, S/I will be larger due to randomization opportunities for arrival patterns and service times at Lock B.

Possible Factors Affecting Lock Interdependence

If all of the lock delay interdependencies were known, one would expect that there would be some conditions that prevailed for interdependent locks. For example, a Pennsylvania State University study classified locks as dependent or independent according to the linehaul distance separating them [Carrol 72]. A methodology that could incorporate those characteristics or "factors" that are most important in determining delay interdependencies would provide for more comprehensive estimation of the evaluation functions.

There are numerous factors that might be related to lock interdependence. Queuing theory is helpful in identifying the most relevant factors. Using an m/g/1 queuing model, the average wait time, W, is found by Whitt [84] to be

$$W = \frac{1}{\mu} + \frac{\rho^2 + \lambda^2 \sigma^2}{2\lambda(1-\rho)} \qquad \text{Eq. 3.11}$$

where μ and λ are the mean service and arrival rates respectively, ρ is lock utilization, and σ is the standard deviation of the service time distribution. In examining this queuing model as well as work by others discussed in Chapter 2, several possible factors relating to delay interdependence may be identified. In a series of locks, if the arrivals at a particular lock are Poisson distributed, then it is likely that the effects from the previous locks have been diluted. In other words, interdependence should be related to the *opportunity* (or lack thereof) for vessels to "randomize" between locks. Linehaul distance, speed (mean and variance), volume, passing opportunities, and network geometry are all likely to affect this opportunity. Similarly, factors may be identified from the service process such as utilization, relative utilizations, tow size distributions, queue discipline, size and number of chambers, and lock reliability.

A Micro-Simulation Model for Waterway Traffic

The stochastic nature of the lock delay problem under assumptions of generalized arrival and service distributions may limit the scope of an analytic model. It is indeed quite difficult to develop expressions for average delays under these conditions while capturing the effects of interdependencies. For this reason, a simulation model proves to be a viable approach to obtaining realistic relationships between certain factors and interdependence among locks. Simulation models are appropriate when a complete mathematical formulation of the problem does not exist or analytical methods require excessively restrictive assumptions.

The Transportation Studies Center at the University of Maryland has developed a microscopic waterway simulation model to analyze the relationships between tow trips, travel times, delays, and lock operations [Dai 89]. The model traces the motion and records the characteristics of each tow (e.g. number of barges, commodity type, speed, origin, destination, direction, and arrival times), while allowing for variability in many of the lock queuing factors such as capacity, volume level, etc.

The model is event scanning, i.e. the status is updated by the occurrence of one of five events 1) trip generation, 2) tow entrance at locks, 3) tow arrival at destinations, 4) lock stall, and 5) end of inventory period. The model places no restrictions on the number of locks, chambers, cuts, waterway links, tows, O-D pairs, and time periods. One limitation of the model, however, is that it currently has only been validated for series network geometry. The

validity of the model has been tested by comparing the model predictions with actual data along five Ohio River locks. Traffic volumes were predicted quite accurately by the model, with an average deviation of 1.53%. The waiting times at locks were predicted within a 10% error. The estimates of these quantities were made without any systematic bias.

Simulation Experiment

As is common with micro-simulation, the simulation model mentioned in the previous section would require a significant time investment for performing an evaluation on numerous combinations of projects. In order to evaluate a combination of projects, it is necessary to compute the total average delays both at current capacity levels and improved capacity levels. Also, for variance reduction purposes, it is desirable to perform numerous runs (approximately 30) for each observation. Because the number of possible combinations of projects may be large, a naive selection and sequencing technique would require the complete evaluation of numerous combinations. For most project proposal sets, using a micro-simulation model alone would be prohibitively expensive.

An alternative to direct application of micro-simulation is to employ the simulation model in an experiment to assess, in functional form, the degree to which certain explanatory factors contribute to lock interdependence. Specifically, an experiment can explore the extent to which delays at a particular lock are affected by changes in the characteristics of other locks. The data generated from such an experiment could be used to estimate functions to be used as a substitute for the simulation model. The function(s) would correspond closely with the function $g(\mathbf{Y})$ in Eq. 3.9. A model estimated from simulated data is termed a meta model.

Because queuing delays are the source of interdependence, an experiment was designed involving a system of locks that have the total delay in the system as the *response* variable. As discussed earlier, *factor* variables are then chosen on the basis of queuing theory and the opportunities for vessels to randomize between locks. The factor variables for the simulation experiment are described below:

Distance, D - This variable is the linehaul distance between locks and is likely to be a strong indicator of the opportunity for the spacing between vessels to randomize.

The larger this distance, the greater the vessel spacing randomization and the smaller the degree of interdependence.

Critical utilization, ρ_c - This variable is the maximum volume to capacity ratio in the system and is a measure of the extent to which traffic is "metered" through a critical lock. Poisson distributed traffic (a condition for independence) may be distorted by the metering of traffic at a lock. Therefore a high critical utilization is likely to give rise to interdependence.

Relative utilization, U - This variable is the ratio of the utilization of a given lock to that of the critical lock and measures the extent to which the delays at a given noncritical lock may be dominated by the delays at the critical lock.

Table 2 shows the values associated with each level of the factor variables used in the simulation experiment. The range of values included are derived from typical values observed in the inland navigation system. A combination of values of the factor variables represents a simulation case. For each case, the simulation model must provide the data necessary to compute S/I from Eq. 3.10.

The experiment involves the simulation of various systems of two locks, Lock 1 and Lock 2. The basic system of locks simulated is shown in Figure 6. First, two locks with given levels of the factor variables are simulated as a system, where the interdependence is captured and included in the resulting average delay, (Fig. 6 top). Second, two independent locks with identical levels of the factor variables are each simulated as a one-lock system (Fig. 6 bottom). Specifically, the average total delay must be obtained for the locks acting as a system and for both locks acting independently. The ratio of these two totals is S/I.

Table 2 Values of Factor Variables Used in Simulation Experiment

Level	Linehaul Distance (Miles)	Critical Utilization	Utilization Ratio
1	5	.320	.053
2	20	.660	.369
3	30	.750	.633
4	80	.890	.845
5	-	1.000	-

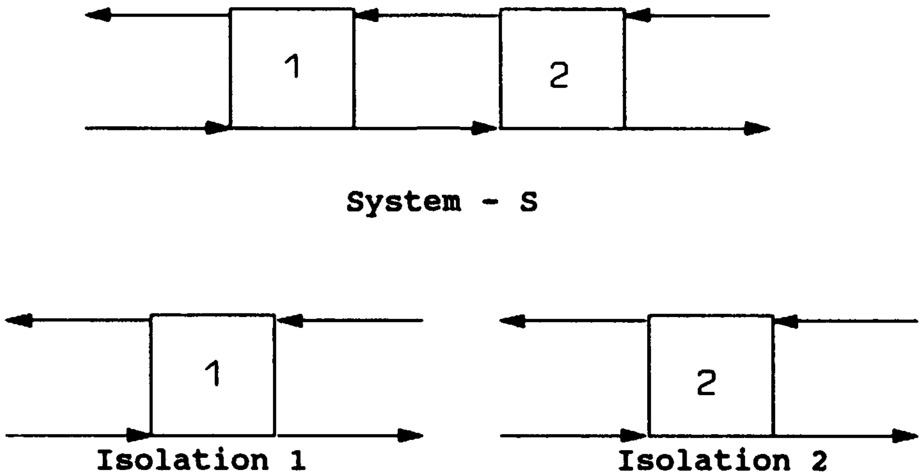

Figure 6 System and Independent Configurations for Simulation

To achieve the various levels of the factors for a two lock system, Lock 1 is considered critical, i.e. it always has the larger utilization. The capacity of Lock 1 is fixed at 60.6 tows per day and the system volume is adjusted to yield the desired utilization. For example, to achieve a critical utilization, ρ_c, of .89, the volume level used in simulation is 53.93 tows per day, since 53.93/60.6 = .89. The desired utilization of the second lock is obtained by the given level of U. For example, if U=.633 and ρ_c = .89, then the utilization of the second lock is .560. The utilization of the second lock is achieved by adjusting its volume. In this case, the volume of Lock 2 would be 33.94 because 33.94/60.6=.56. A summary of the utilizations and volumes of Lock 2 necessary to yield desired combinations of U and ρ_c is provided in Table 3.

An assumption of this simulation experiment for estimating evaluation functions is that the only geometric configuration considered is a series of locks. This assumption is reasonable given the near tree-structure of the inland waterway network. A possible expansion of this methodology would include simulation of the junction points.

Table 3 Summary of Volume and Utilizations for Lock 2

U \ $\rho c1$	0.890		0.750		0.660		0.320	
	$\lambda 2$	$\rho 2$	$\lambda 2$	$\rho 2$	$\lambda 2$	$\rho 2$	$\lambda 2$	$\rho 2$
1.000	53.93	.890	45.45	.750	40.00	.660	19.39	.320
0.845	45.45	.750	38.36	.633	33.94	.560	16.36	.270
0.633	33.94	.560	28.78	.475	25.33	.418	12.24	.202
0.369	20.00	.330	16.36	.270	14.54	.240	7.27	.120
0.053	2.85	.047	2.18	.039	2.12	.035	1.03	.017

The number of required simulation runs for the experiment may be significantly reduced if an adequate function for a series of n locks may be obtained from simulation data based on a series of only two locks. Assuming that such a technique is successfully obtained, the number of simulation observations required, O_s, for a two-lock series is

$$O_s = 2*l_1(l_2)(l_3)(l_4) = 480 \qquad \text{Eq. 3.11}$$

where l_i is the number of levels of factor i. The number of independent simulation runs per observation was chosen to be 30 in order to sufficiently reduce the simulation variance. Experiments using less than 25 runs per observation were found to have variances that were excessive. Finally, to determine the required simulation time period for each run, a series of simulation trials were conducted. With each trial, the number of simulation days per runs is increased until steady-state conditions are achieved and variances are within prespecified tolerance levels. The minimum number of tows required per simulation run to achieve this objective is on the order of 1300.

Methodology for Project Sequencing and Scheduling

Prescreening of Projects

Nearly any solution procedure for project sequencing and scheduling would benefit from a prescreening process that could simplify the problem by reducing the size of the

possible solution space. While problem reduction should not be a prerequisite for a solution procedure, it should be considered wherever possible. For example, Pearman [79] noted:

> *A very important objective for research in this area is to switch attention away from the set of all physically and budgetarily feasible solutions as the basis for comparison towards an investigation only of those solutions which are, in some sense, locally optimal...By restricting attention to locally optimal solutions, valuable insights about the relationships between local optima and global optimum, and hence about desirable structures for search procedures, could emerge.*

One very effective means of reducing the size of the solution space for the project sequencing problem is the decomposition of the solution set. As mentioned in Chapter 1, the number of possible project sequences from N projects is N!. The size of the solution space, therefore, grows nonlinearly with N. From the behavior of the factorial function, we know in general that

$$N! >> \sum_i (n_i\ !) \qquad \text{Eq. 3.12}$$

where n_1, n_2, ... are mutually exclusive subsets of N projects. This property implies that decomposing the project set into clusters of mutually independent projects has great potential in reducing the size of the overall solution space. Clusters may be defined by identifying those project subsets where each project 1) interacts with at least one other project in the subset and 2) is independent of all projects in other subsets. For example, for 10 projects there are 10! or 3,628,800 possible sequences. If the 10 projects are decomposed into two sets of five projects, then the number of possible sequences is only (5! + 5! + 10) = 250.

Because the number of possible project sets increases nonlinearly with N, the possibility of eliminating projects could disproportionally reduce the size of the solution space. To examine the effects of reducing the project set by one on the number of possible sets, note that

$$N! - (N-1)! = (N-1)\ (N-1)! \qquad \text{Eq. 3.13}$$

Therefore, given a reasonably large N, if the project set is reduced by one, then the solution space is reduced by much more, namely by (N-1) (N-1)!. The advantages of clustering

go beyond potential computational reductions. It is helpful to identify where segments of the waterway system may be subdivided for purposes other than investment planning.

Project Sequencing Procedure

The approach for searching the solution space of possible project permutations involves representing the solution space in two dimensions and applying a search algorithm in selecting the preferred sequence. Given a system cost evaluation function for interdependent projects $g(\mathbf{Y})$, the selection and sequencing problem may be represented in two dimensional space. Assuming that each set of projects may be viewed as a system generating a common time-dependent output, then a two dimensional representation is quite feasible. For the lock rehabilitation problem, the costs associated with a given combination of projects in a given time period t, may be written as

$$(SC)_t = C_i A_{rh} + g(\mathbf{Y},\mathbf{D},\mathbf{U},\lambda,\rho_c)_t O_W \qquad \text{Eq. 3.14}$$

where C_i is the total capital cost of construction for project i and A_{rh} is the capital recovery factor for the given interest rate, r, and planning horizon, h. The term $g(\mathbf{Y},\mathbf{D},\mathbf{U},\lambda,\rho_c)_t$ represents the delay, and corresponds to the function(s) obtained from the simulation experiment and O_W is the opportunity cost of delay. Evaluating SC at different levels of output for a combination of projects Y, defines a curve with annual system costs SC_t on the vertical axis and output level, λ, on the horizontal axis. Repeating for different values of $\mathbf{Y}$ (project combinations) produces a family of curves whereby a sequencing and scheduling decision path is defined. Because the output is assumed to be time dependent, the horizontal axis may also represent time periods, e.g. years. Output and time may be linked through a demand function, $\lambda(t)$.

Consider an example with interdependent projects A, B, and C. Figure 7 shows a family of system cost (SC) curves corresponding to the possible combinations of these three projects. Note that in general, combinations involving only one project are favorable (lower SC) for low levels of output (thus earlier in the horizon stage), and become less favorable as output increases. Under this representation, one combination is preferred to another at a given output level (or time period) if its corresponding curve lies above the other.

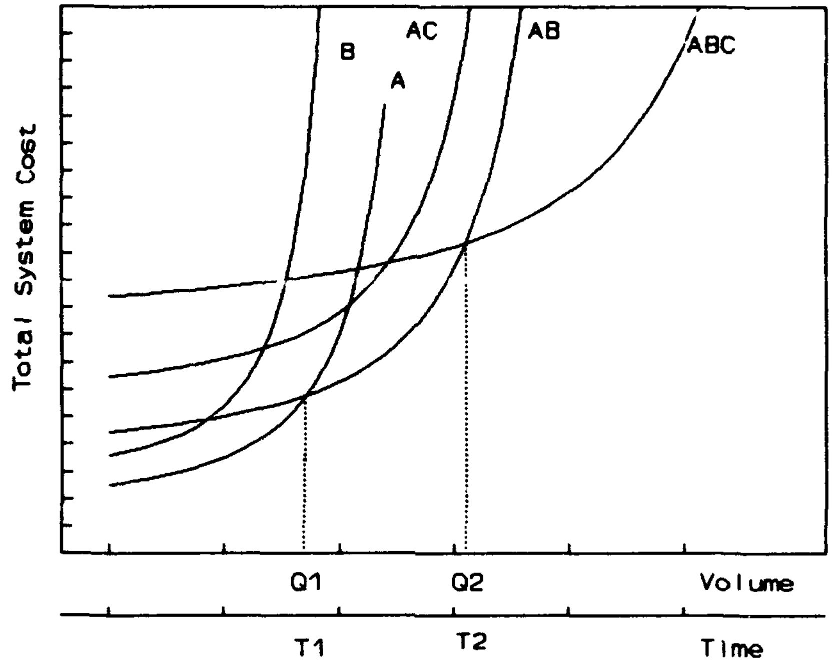

Figure 7 Plot of System Cost for 3 Interdependent Projects (Case 1)

In the example depicted in Figure 7, the selection and sequence of projects is dictated by the lower "envelope" defined by the curves. Here, all three projects would be accepted if the volume level is expected to eventually exceed Q_2. We see also that the sequence of projects should be A, B, C; this is because Curve A lies above B and C, and AB lies below AC in the relevant regions. Project A is preferred until volume level Q_1 upon which Project B should be implemented corresponding to curve AB. At volume level Q_2, Project C should be implemented corresponding to Combination ABC. Depending on the relationship between output and time, this representation could provide some insight into the scheduling problem as well.

A second case involving three projects is shown in Figure 8. Here, because Curve AB lies completely below Curve ABC, only Projects A and B are included in the program. The sequencing decision would be the same as in the previous example with the intersection of Curves A and AB indicating that the implementation of Project B should be timed at t_1.

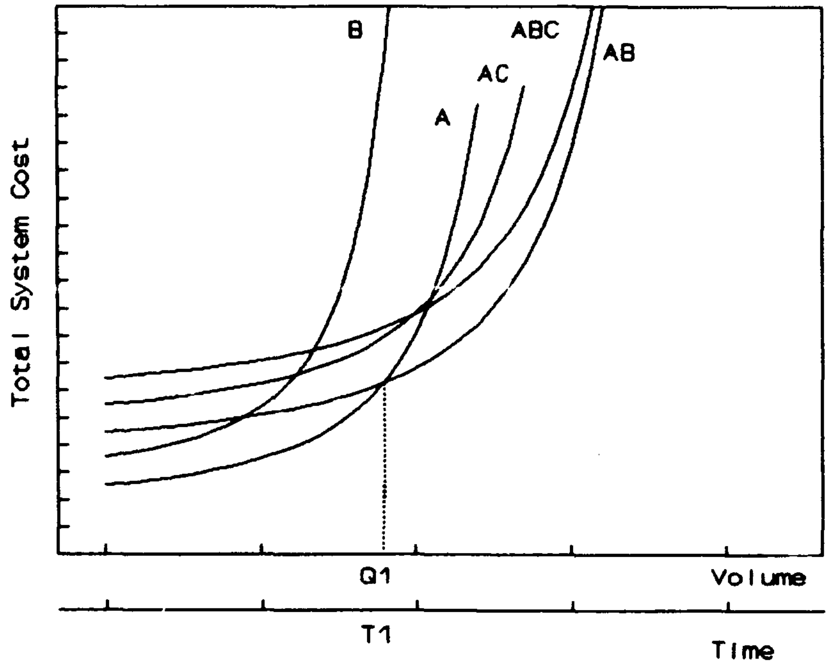

Figure 8 Plot of System Cost for 3 Interdependent Projects (Case 2)

It is not necessary to graph all of the combinations. For example, in Figure 8 the curves representing Combinations C and BC have been omitted because they would both lie completely above Combination A. In other words Projects B and C could only be included in the implementation plan following Project A.

Unfortunately not all such families of curves can be interpreted as easily as Cases 1 and 2. Consider a third case shown in Figure 9 where Curves A and AB are unchanged but the others are different. Here, Curves AB and AC intersect each other before intersecting Curve ABC. It cannot be stated a priori whether Combination AB or AC should be selected. One would expect that if Area 1 is greater than Area 2, then Combination AB is preferred to BC and Project B should precede Project C on the expansion path.

Identifying when one combination "dominates" another is one of the most important questions to be explored when considering such a two dimensional approach. A criterion for dominance determines to what extent certain combinations may be eliminated from consideration. For example, it is likely that information regarding the dominance of certain projects over others could be used to eliminate projects

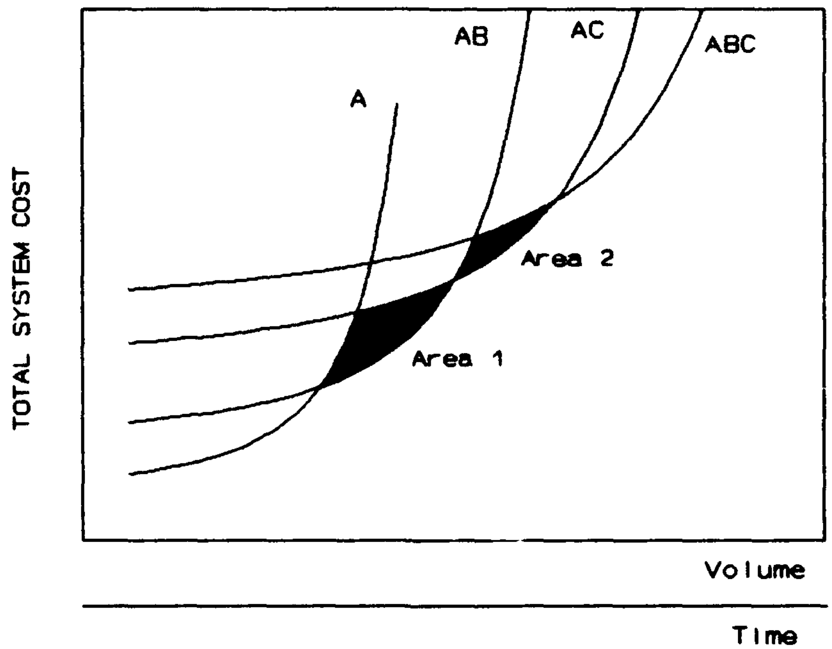

Figure 9 Plot of System Cost for 3 Interdependent Projects (Case 3)

from the solution space. By eliminating combinations, the solution procedure may reduce the solution space to one more easily searched.

Under the assumption that the benefits associated with a given combination of projects vary only with the output of the system, the start dates of the projects do not have an effect on the system costs in each of the time periods. The implications in the context of waterways are that the capital cost of construction, operating and maintenance costs, and benefits from reduced delays are not affected by the age of the locks at any given time (i.e. by project start dates) but only by the volume of traffic using the locks. This assumption is very reasonable for the capital costs, but somewhat simplifies the operating and maintenance costs. The assumption is also reasonable for delay benefits although it neglects the effect of long term economic changes induced by the presence and performance of waterway investments.

Incorporating a Budget Constraint

The representation of project combinations proposed thus far has not incorporated the effects of a budget constraint. In structuring the budget constraint, it will be assumed that funds not spent in a given period will be available in subsequent periods. This is the case represented by Eq. 3.2 and by the Inland Waterways Trust Fund. For example, if $5 million is available in Period 1 and nothing is implemented in Period 1, then the $5 million is added to the budget limit for Period 2. Under this assumption, budget limitations have the effect of delaying the earliest feasible start date of a given project combination, just as they limit the earliest start of an individual project.

Consider the small example of two projects A and B. In constructing the Curves A, B, and AB, the infeasible portion must not be included. Figure 10 illustrates that the combination A is not financially feasible until time T_1 corresponding to output Q_1. Combination AB is not feasible until time T_2. The three possible expansion paths are then as follows:

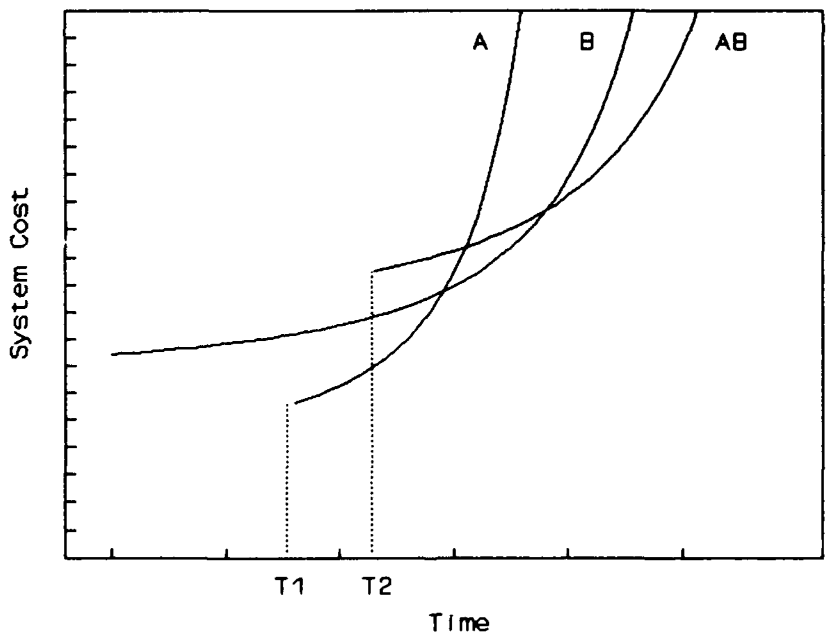

Figure 10 Incorporating a Budget Constraint

1. start A at time T_1 and B when Curves A and AB intersect, T_2

2. start B immediately and A when Curves B and AB intersect, T_3.

The problem of selecting the optimal schedule of interdependent projects is combinatorially large and currently not solvable by a polynomial-time algorithm [Akileswaran 83]. A significant contribution of this research is the development of a methodology for searching through the vast solution space. The approach discussed in this Chapter is to estimate evaluation functions from simulated data and then represent the solution space in two dimensions. The two dimensional representation provides a framework for immediately applying some search techniques for many instances of the problem.

Summary

The methodology for investment planning of interdependent lock improvements is divided into two phases. The first phase is the development of evaluation functions that may act as a substitute for a microsimulation model for waterway traffic. The evaluation functions represent the combined delay and capital costs for a series of interdependent locks. These functions are estimated based on a simulation experiment involving a two lock system. The experiment is conducted over three factor variables, and four levels of each factor. Simulated delays are compared between 1) the two locks acting interdependently as a system, and 2) the same two locks acting independently in isolation. The ratio of these delays, S/I, is a measure of interdependence in the system. Functions are then estimated from the resulting data from the simulation experiment.

The second phase employs the evaluation functions to compare various combinations of project implementations over time. By plotting the system costs as determined by the evaluation functions, different implementation combinations may be superimposed for comparison. The superposition of combinations defines a lowest cost expansion path simultaneously yielding the costs (evaluation), sequence, and start times (schedules) of project implementations. The searching for the optimal or near optimal expansion path may be performed heuristically. The heuristic must consider the possibility of expansion conflicts, i.e. when the path implies a temporary removal of previously accepted projects.

CHAPTER 4
EVALUATION OF INTERDEPENDENT LOCK IMPROVEMENTS

In this Chapter, the methodology presented in Chapter 3 for evaluating interdependent lock improvement projects is implemented. The data produced from the simulation experiment are used to estimate an evaluation function for a two lock system. An analytical coupling technique is employed to expand the function to incorporate systems of n locks. An experimental validation of the coupling technique is then performed. The expanded function is then used to derive some properties of locks regarding interdependence. Finally, a cluster of hypothetical proposed lock improvements are evaluated as an illustration of the use of the functions.

Simulation Results

While a complete set of the compiled simulation output is provided in Appendix 1, Table 4 provides a sample of the data for utilization ratio of 1.00 and critical lock utilization of 0.89. Specifically, mean isolated and system waiting times are reported for each of the two locks for all three distance levels for directions 1 and 2. Also included are the total system and isolated delays for both locks over both directions. Finally, the corresponding value for the interdependence coefficient, S/I, is computed from the total system and isolated delays from traffic in both directions.

Lock 1 was kept as the critical lock throughout all simulation observations and the volume of Lock 2 was changed accordingly in order to obtain variable values of U. All the required simulation input parameters discussed in Chapter 2, e.g. the mean and variance of tow speeds, tow cut size, and tow size were available from the Performance Monitoring System data.

Theoretical Boundaries

When using simulation, it is both necessary and helpful to examine the resulting output for consistency with established theory. In the case of delays at lock sites, queuing theory provides guidelines whereby the results of the simulation may be checked. One such boundary is that the interdependence factor, S/I may not be less than 0.5 (1/n where n is 2 locks) and greater than 1.0. The lower bound condition is derived by assuming a deterministic

Table 4 Results of Simulation for U=1.00 and ρ_C=.89

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Tot. I	Tot. S	S/I
	Dir 1	47.184	33.362	47.184	34.336			
5	Dir 2	46.856	33.337	46.856	34.006	94.04	67.52	0.7180
	Dir 1	47.184	38.008	47.184	37.824			
20	Dir 2	46.856	37.414	46.856	41.562	94.04	77.40	0.8231
	Dir 1	47.184	39.477	47.184	40.046			
30	Dir 2	46.856	40.721	46.856	38.928	94.04	79.59	0.8463
	Dir 1	47.184	43.751	47.184	44.038			
80	Dir 2	46.856	45.177	46.856	45.091	94.04	89.03	0.9467

U = 1.00

Lock 1: V/C = 0.89
Lock 2: V/C = 0.89

system with equal service times where gaps between vessels do not randomize during the linehaul portions of waterway channels. From the tabulated results, it can be seen that with only two exceptions, the values for S/I are within the theoretically specified range, i.e. they are slightly > 1.0.

In the two exceptions where the upper bound is exceeded, the relative utilization is low and the distance is high. These preliminary checks serve as a partial validation of the experiment.

Exploratory Data Analysis

The data are plotted in Figures 11 through 16 with S/I on the vertical axis and utilization of the critical lock on the horizontal axis. Each point in the plots represent the average of 30 runs. These plots are helpful in making first assessments of the functional form of the interdependence coefficient. It appears from these plots, that the upper bound on S/I is slightly less than 1.0 and that it decreases at an increasing rate with the utilization of Lock 1. There is a noticeable relationship between the level of interdependence and both the critical utilization and distance. The exploratory analysis suggests that a functional model for S/I should include relative utilization, critical utilization, and distance between locks as variables.

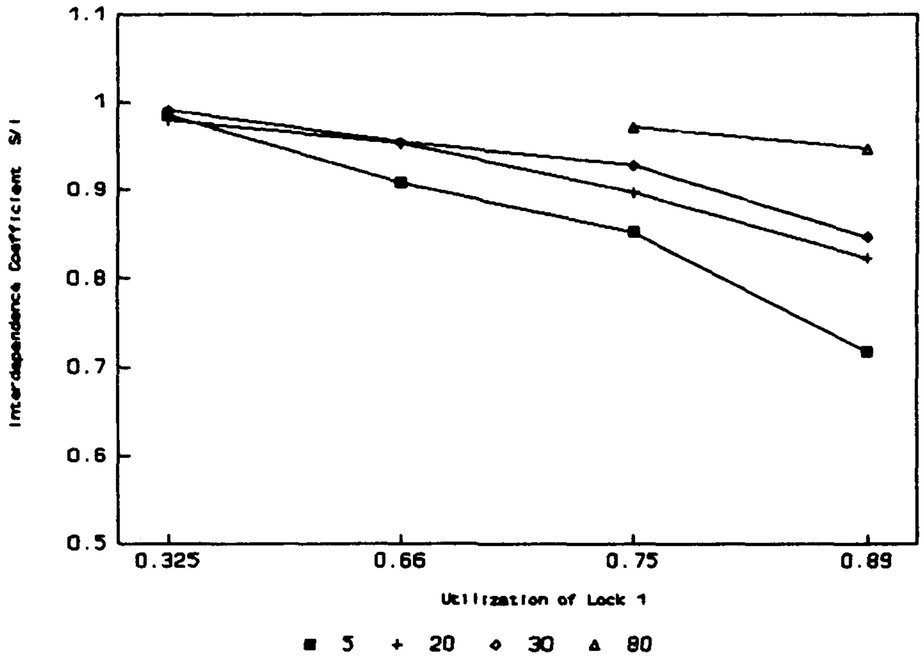

Figure 11 Simulation Results for U=1.00

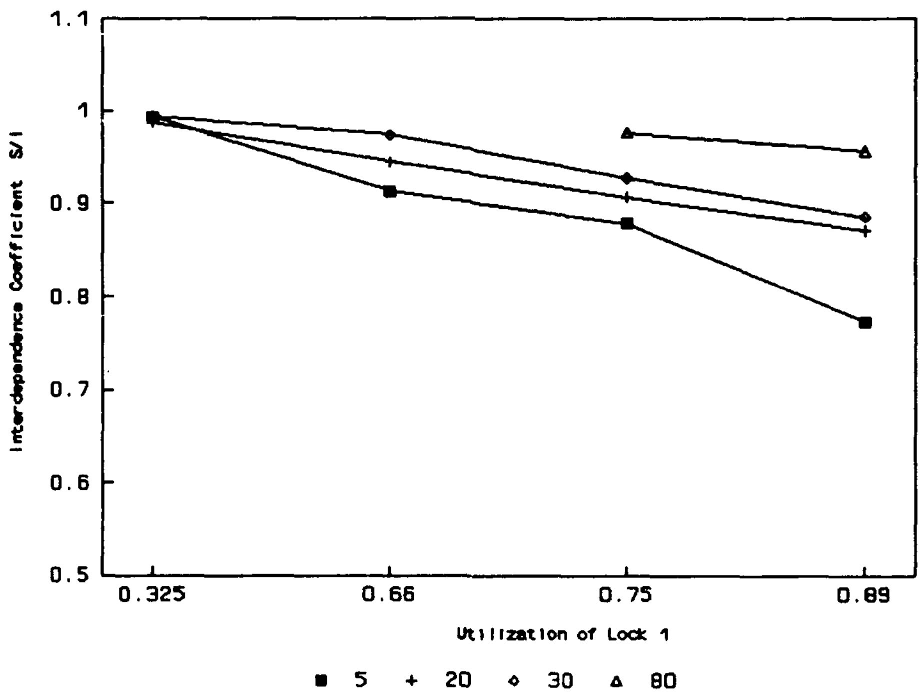

Figure 12 Simulation Results for U=0.89

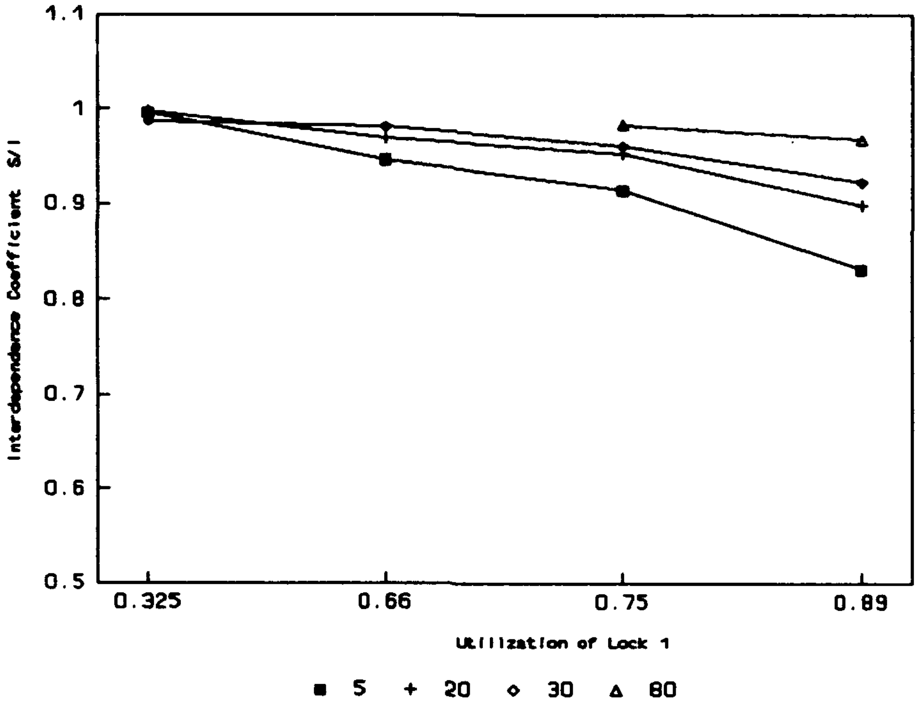

Figure 13 Simulation Results for U=0.633

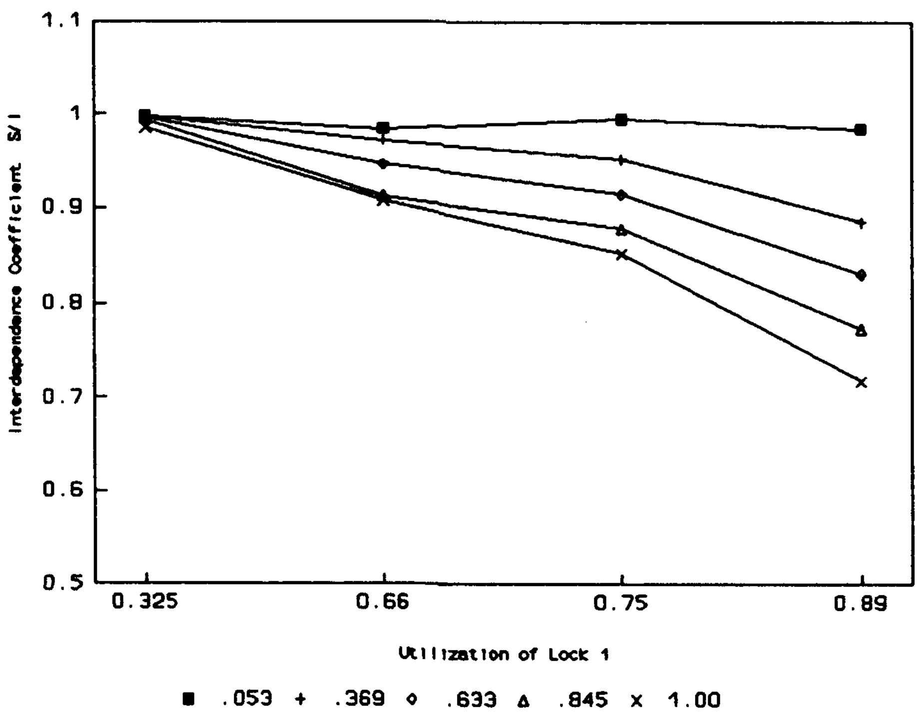

Figure 14 Simulation Results for D=5

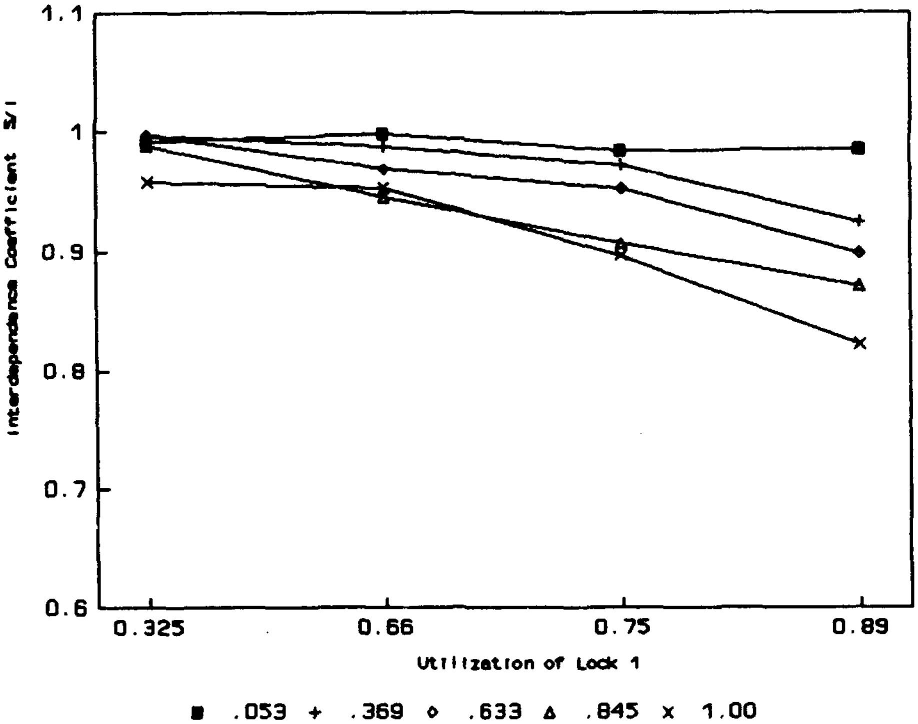

Figure 15 Simulation Results for D=20

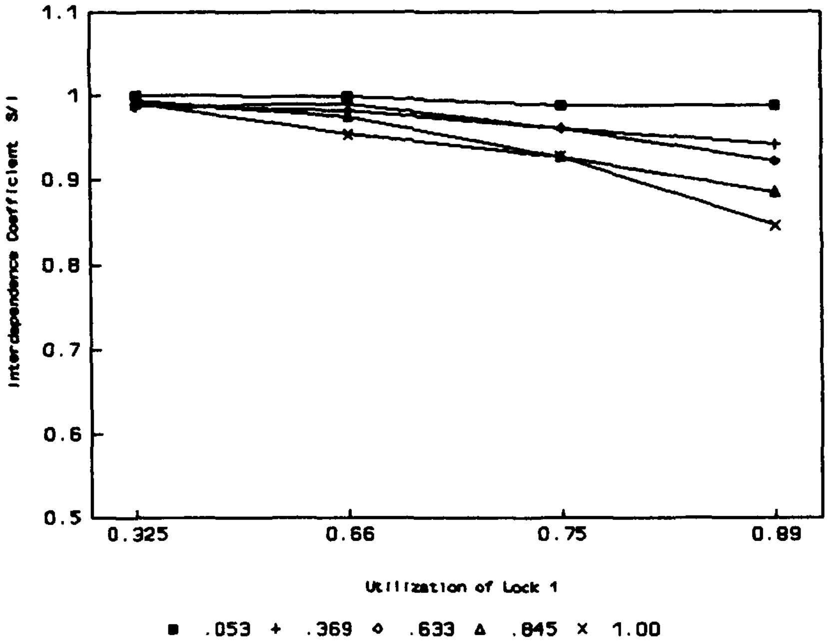

Figure 16 Simulation Results for D=30

The simulation output suggests that as the distance between two locks *increases*, the amount of interdependence among those locks also *increases* (S/I decreases). This result is consistent both with earlier studies, [Carrol 72] and hypotheses. In Chapter 3, it was mentioned that lock interdependence is inversely related to the opportunities for the intervals of vessels to randomize. Intuitively, the distance between locks would tend to increase the randomization of traffic. On the other hand, distance may not be the predominate influence on interdependence as some studies suggest. For example, in Carrol [72], distance was the only variable considered. Based on these results, it appears that the critical utilization has a more significant effect on interdependence than distance.

Functional Estimation for S/I

S/I Model Formulation and Calibration

In this section, a mathematical function that is adequately consistent with the compiled simulation data is derived. It is possible that the functional form of the interdependence coefficient is nonlinear in terms of the variables suggested, with an upper bound of 1.0. However, since a lower bound of 1/2 is based on a deterministic system, it may not be used in establishing a functional form. While the statistical tools for estimating parameters for nonlinear relationships are less versatile than those for linear relationships, least squares regression and maximum likelihood are often quite effective in nonlinear estimation, once a functional form has been specified. A functional form that yields 1.0 at a volume level of 0 and decreases faster than linearly with critical utilization would seem to closely fit the data as plotted. One tractable mathematical form expressing such a relation is given below:

$$(S/I) = 1 - \alpha \, \rho_c^{\beta} \, U^{\gamma} \, D^{\delta} \qquad \text{Eq. 4.1}$$

Expanding the ρ_c and U terms for locks labeled 1 and 2 we obtain:

$$(S/I) = 1-\alpha \, (\max(\rho_1,\rho_2))^{\beta} \, [\min(\rho_1,\rho_2)/\max(\rho_1,\rho_2)]^{\gamma} \, D_{12}^{\delta} \qquad \text{Eq. 4.2}$$

This relation may be interpreted to have an upper bound of 1.0 with the second term representing a quantity of interdependence to be subtracted. Conceptually, $\alpha \max(\rho_c)^{\beta}$ represents the maximum interdependence that may be possible, while U^{γ} and D^{δ} are multipliers that determine the portion of the possible interdependence that may be realized. The

interdependence coefficient may then be used to compute the total system delay of a two lock system, S_{12}.

$$S_{12} = (S/I)\ (I_1 + I_2) \qquad \text{Eq. 4.3}$$

In Eq. 4.3, I_1 and I_2 are the delays of the first and second locks acting in isolation, respectively. Section 4.4.1 discusses how the values for I_1 and I_2 may be estimated.

While the functional form for S/I is nonlinear, it is exponential and subject to logarithmic transformation. With the following substitutions, an equivalent linear model may be formulated.

$$y = \log(1-S/I)$$
$$a = \log \alpha$$
$$x_1 = \log \rho_c$$
$$x_2 = \log U$$
$$x_3 = \log D$$

$$y = a + \beta x_1 + \gamma x_2 + \delta x_3 \qquad \text{Eq. 4.4}$$

The estimation results for this model are shown in Table 5. Converting the transformed variables to their original form yields the following estimated model for the interdependence coefficient of a two- lock system

$$S/I = 1 - 0.713\ (\rho_c)^{2.455}\ U^{0.944}\ D^{-0.506} \qquad \text{Eq. 4.5}$$

Table 5 Estimation Results for the Two Lock System

Independent variable	Coefficient	Std. Error
Log α	-0.146715	0.159294
Log ρ_c	2.455429	0.258661
Log U	0.944259	0.089721
Log D	-0.505525	0.104652

The .95 confidence interval for each of the parameter estimates is given in Table 6.

Table 6 Confidence Intervals for S/I Parameter Estimates

Independent Variable	Estimate	Lower Limit	Upper Limit
Log α	-0.14671	-0.46483	0.17140
α	.71332	0.34290	1.48388
Log ρ	2.45543	1.93888	2.97198
Log U	-0.50553	-0.71452	-0.29653
Log D	0.94426	0.76508	1.12343

Model Diagnostics

The objectives of performing model diagnostics are 1) to assure that the estimation of the parameters are within acceptable tolerances, 2) to assure that the assumptions of the estimation technique have not been violated and 3) to assure the usefulness of the model.

The estimated values for parameters α, β, γ, and δ are 0.713, 2.455, 0.944, and -0.506 respectively. These values are consistent with the physical parameters of the problem. For example, the negative value for δ suggests that S/I increases with distance, while the positive values for β and γ suggests that S/I decreases with both critical utilization and relative utilization. As will be shown in other sections, the plot of the function is consistent in form to that shown in the exploratory data analysis.

Figure 17 shows a plot of the observed values of y, log(1-S/I), versus the predicted values. The plot suggests an overall good fit of the model to the data. Further, the fit appears to be exceptionally good for high values of y. Because interdependence is most prevalent at high values of y, the fit for high values of y is more critical. The simulation data show that the amount of interdependence is nearly insignificant at small values of y. Because the fitted line does not appear to be skewed by the data for lower values of y, it appears unnecessary to reestimate the portion of the data corresponding to the larger values of y in hopes of achieving a more reliable model.

The analysis of variance for the regression is shown in Table 7. The high F ratios suggest a very high level of significance for each of the model variables. The coefficient of correlation, R^2, which measures the

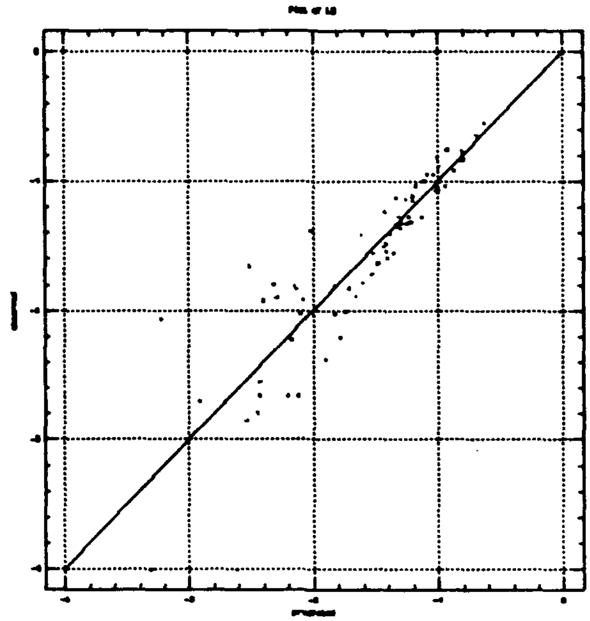

Figure 17 Predicted vs. Observed Values for y

Table 7 Analysis of Variance for S/I Calibration

Source	Sum of Squares	DF	Mean Sq.	F-Ratio
Log ρ	9.3649	1	9.364943	77.28
Log U	13.4227	1	13.422738	110.76
Log D	2.8277	1	2.827771	23.33
Model	25.6155	3	8.538480	70.46
Error	7.9982	66	0.121185	

R^2 = 0.762054

proportion of sum of squares variation that is explained by the model, is .751 after adjusting for degrees of freedom. The correlation matrix, Table 8, reveals that while there is a significant correlation among the distance and constant, there is little correlation among the three model variables.

The primary assumptions in calibrating the model have been that the observations are independent and that the residuals are normally distributed with mean zero and constant variance. Computations of the residuals show that their mean is zero, while the probability plot in Figure 18 suggests that the normality assumption is valid. A plot of the standardized residuals shows that the variance is larger for small values of y, Figure 19. While the assumption of constant variance may not be entirely valid, a weighted regression did not change the values of the coefficients significantly.

Table 8 Correlation Matrix for S/I Calibration

	Log α	Log ρ	Log U	Log D
Log α	1.0000	.4600	.2231	-.8859
Log ρ	.4600	1.0000	.0000	-.1727
Log U	.2231	.0000	1.0000	.0000
Log D	-.8859	-.1727	.0000	1.0000

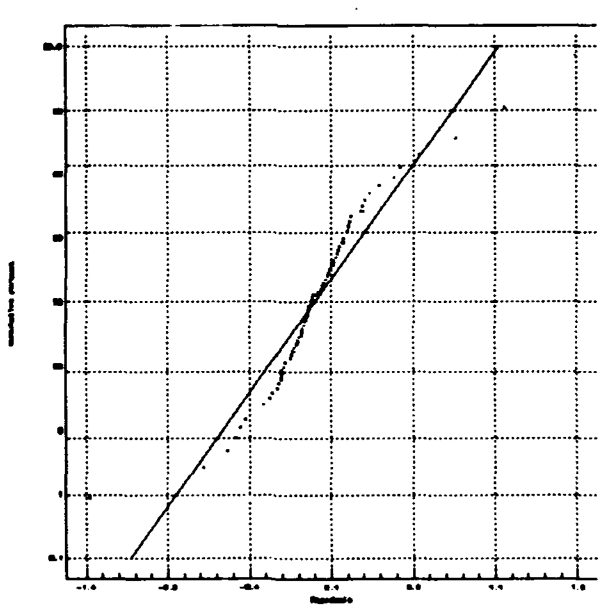

Figure 18 Normal Probability Plot of Residuals

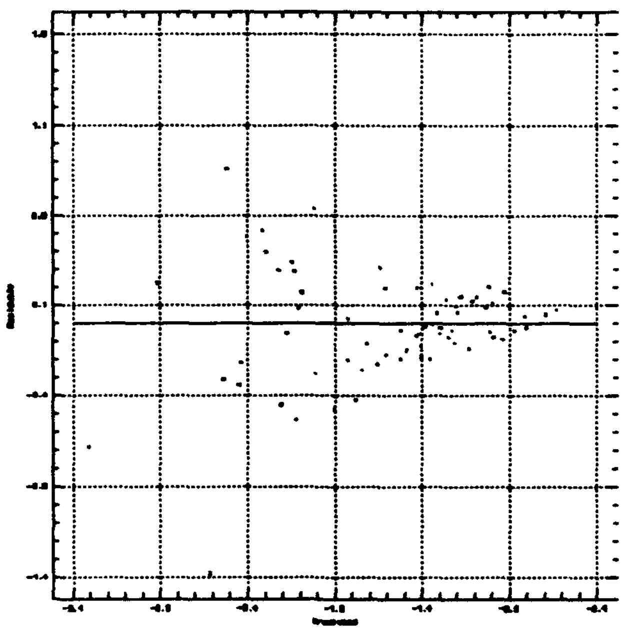

Figure 19 Plot of Standardized Residuals

Approximate Analytic Validation

Although the model diagnostics for the S/I model are satisfactory, it is sometimes helpful to perform some analytic approximation of a problem to provide validation to the functional form and range of the statistically estimated model. However, as expected, certain assumptions and limitations in the scope apply. Using queuing theory [e.g. Wolff, 1989], an approximate analytic expression for S/I may be derived for providing some validation to the model calibrated in Chapter 4.

The approximation is limited to a two-lock system as shown in Figure 20. Associated with each lock is an arrival process, departure process, and service time variance. Because the first lock is considered independent from any previous locks, an m/g/1 process (i.e. Poisson distributed arrivals/generally distributed service times/one server) may be reasonably assumed. If the two locks were independent, the second lock would also have an m/g/1 process. However, because the locks are not independent, the arrivals at the second lock are in some way related to the departures at the first lock. Therefore a more complex g/g/1 (i.e. general arrivals/general service times/one server) process must be used in modeling the second lock.

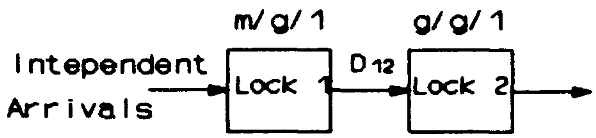

Figure 20 Two Lock System for Analytic Approximation

For this system, an initial expression for S/I is immediately available from the definition,

$$S/I = \frac{(W_{m/g/1})_1 + (W_{g/g/1})_2}{(W_{m/g/1})_1 + (W_{m/g/1})_2} \qquad \text{Eq. 4.6}$$

where the numerator in Eq. 4.6 represents the total average delay of the two locks acting as a system, while the denominator represents the total average delay of the two locks acting in isolation. Queuing theory is helpful in solving for the $W_{m/g/1}$ terms. However a further assumption is necessary in solving for $W_{g/g/1}$. Using the stationary interval method, Whitt (1984) has obtained the following closed-form solution for $W_{m/g/1}$:

$$W_{m/g/1} = \frac{1}{\mu} + \frac{\lambda + \lambda^2 (\sigma_s)^2}{2 \lambda (1-\rho)} \qquad \text{Eq. 4.7}$$

The term σ_s is the standard deviation of service time and is assumed to be independent of the queuing process. Values of σ_s in the range of (0.4,2.0) hours are typically observed, and a value of 1.2 will be specified for this analysis. Therefore, all terms in Equation 4.7 are given or can be obtained.

While no closed-form solution exists for $W_{g/g/1}$, one reasonable approximation is available from the Kraemer and Langenback-Belz formula [Whitt 84]

$$W_{g/g/1} = \frac{1}{\mu} + \frac{\{\lambda(\lambda^2 (\sigma_a)^2 + \lambda^2 (\sigma_s)^2\}E}{2 \mu^2 (1-\rho)} \qquad \text{Eq. 4.8}$$

where

$$E = \exp\{-(1-\rho) (\lambda^2(\sigma_a)^2-1)/(\lambda^2(\sigma_a)^2 + 4\lambda^2(\sigma_s)^2)\}.$$

The standard deviation of service time, σ_s, is also specified to be 1.2 for the g/g/1 lock. All the parameters in Equation 4.8 are directly obtainable except for the standard deviation of the arrival rate for the second lock, σ_a. To obtain σ_a, it is first necessary to note that a closed form expression for the standard deviation of the departure process, σ_d, for an m/g/1 queue has been shown to be [Whitt 84]

$$(\sigma_d)_{m/g/1} = ((\sigma_s)^2 + (1-\rho^2)/\lambda^2)^{1/2}. \qquad \text{Eq. 4.9}$$

If it is assumed that the distance between the two locks is zero, then σ_a for the second lock (g/g/1) will be equal to σ_d for the first lock (m/g/1).

It is now possible to compute S/I for the two-lock system shown in Figure 20. To test the functional form of the model, S/I is computed with respect to increasing values of the critical utilization, ρ_1 and relative utilization ρ_1/ρ_2. This is achieved by letting λ increase uniformly by 1.0 with each observation and μ_2 increase uniformly by 3.0 with each observation. Table 9 reports the results of six observations of this nature. As with the observations for the simulation experiment, the capacity of the first lock is fixed while volume and the capacity of the second lock are increased to generate increasing values in ρ_1, ρ_2, and U. The results show a fall in S/I with respect to these three parameters.

The plot in Figure 21 shows that, as with the metamodel, the fall in S/I increases sharply for high values of ρ. The analytic approximation does differ in some respects to the metamodel however. Specifically S/I does not exceed 0.65 and falls much lower than any case obtained

Table 9 Six Observations Using Analytic Approximation

λ	μ_2	ρ_1	ρ_2	U	$(W_{m/g/1})_1$	$(W_{m/g/1})_2$	$(W_{g/g/1})_2$	S/I
13	33	0.65	0.39	0.61	37.14	21.42	1.859	0.647
14	30	0.70	0.47	0.68	43.32	24.71	3.448	0.648
15	27	0.75	0.56	0.75	51.97	29.78	6.492	0.646
16	24	0.80	0.66	0.82	64.95	38.17	12.592	0.638
17	22	0.85	0.76	0.90	86.59	55.04	26.861	0.618
18	21	0.90	0.87	0.97	129.88	102.90	72.331	0.562

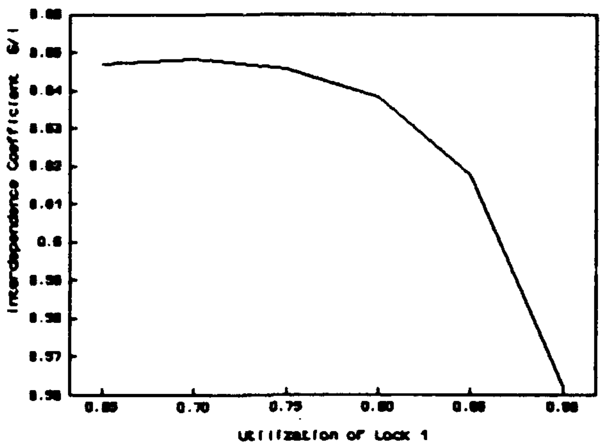

Figure 21 Plot of S/I for Analytic Approximation

empirically. There are two explanations for these differences. First, by assuming a distance of zero, the S/I is systematically reduced. Second, there are variables representing opportunities for randomization among tows that are included in the simulation model that are not included in the analytic model; recall that S/I increases with randomization among tows.

Expanding from Two Locks to n Locks

Parameters of an n-Lock System

Earlier it was shown that the quasi-exponential model for the interdependence coefficient, S/I, is sufficiently consistent with the results of the simulation experiment. Thus, for two lock systems, a satisfactory function may be developed to evaluate interdependent projects without the use of simulation. However, it is likely that groups of locks in a series of three or more, are interdependent. In this section, a procedure for expanding the functional relationship for interdependent 2-lock systems to n-lock systems, such as shown in Figure 22, is described.

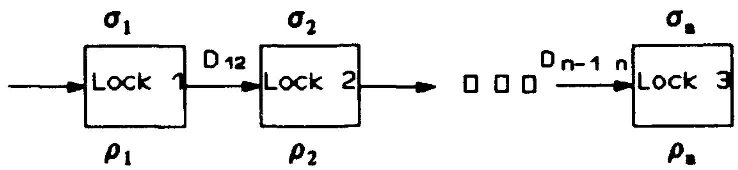

Figure 22 Series of n Interdependent Locks

One possible method is to sum the interdependence among the successive pairs in the system. To illustrate, Y_{12} is substituted in place of the second term in the expression for the interdependence coefficient and a subscript added to denote the number of locks in the system. The variable Y may be referred to as the interdependence variable since it represents the amount of interdependence among locks.

$$Y_{12} = \alpha\ (\rho_c)^{\beta}\ (U_{12})^{\gamma}\ (D_{12})^{\delta} \qquad \text{Eq. 4.10}$$
$$(S/I)_2 = 1 - Y_{12} \qquad \text{Eq. 4.11}$$

It follows that the coefficient for the three lock system would include a term for the interdependence between Locks 2 and 3.

$$(S/I)_3 = 1 - (Y_{12} + Y_{23}) \qquad \text{Eq. 4.12}$$

Summing interdependence in this way has some shortcomings however. First, the technique does not incorporate the variance in lock service times. Second, the interdependence among nonadjacent locks is not accounted for. In addressing these shortcomings, some explanation of the queuing nature of independent locks is required.

Queuing Nature of Independent Locks

In an isolated series of n locks, the first lock is independent from any previous lock. Therefore, the waiting time at the first lock may be described by either an m/g/1 queuing model, as shown by Burke's Theorem, or by a model estimated from simulation results for isolated locks. All other locks in the series will have a significantly more complex g/g/1 arrival process. If an m/g/1 process is assumed for the first lock, then the waiting time is expressed in Eq. 4.13.

$$W_{m/g/1} = \frac{\rho}{\lambda} + \frac{\rho^2 + \lambda^2\ \sigma^2}{2\ \lambda\ (1-\rho)} \qquad \text{Eq. 4.13}$$

It may be more accurate to estimate a function for the delay at an independent lock from the simulation data. Figure 23 is a comparative plot between the delays for an m/g/1 lock and the simulated data. From the figure it is evident that while the two functions have similar forms, the delays from the simulation are noticeably less at low utilization values, and greater at high utilization values.

One functional form that includes the same parameters as the theoretical expression for M/G/1 is the following:

$$W_I = \lambda^a (1-\rho)^b \sigma^c \qquad \text{Eq. 4.14}$$

Like the theoretical expression for M/G/1, this function is asymptotic to the capacity as shown by the $(1-\rho)$ term. The parameters for this function were estimated using the simulated data. Because this model is exponential, it also is subject to logarithmic transformation. The following substitutions are made to transform Eq. 4.14 into a linear model.

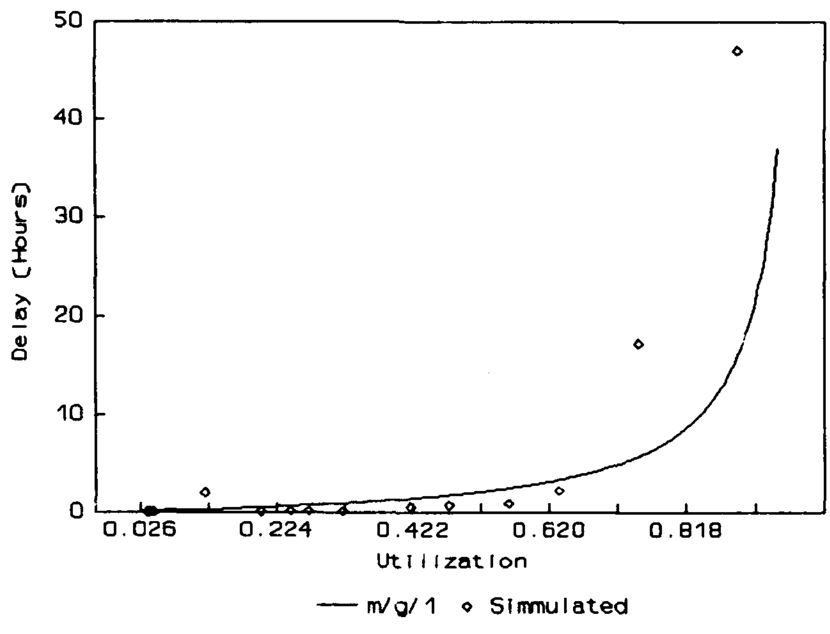

Figure 23 Observed Isolated Delays Compared to the m/g/1 Process

$y = \log W_I$
$x_1 = \log \lambda$
$x_2 = \log \rho$
$x_3 = \log \sigma^2$

$$y = ax_1 + bx_2 + cx_3 \qquad \text{Eq. 4.15}$$

The estimated values for the parameters of the isolated delay model are shown in Table 10 yielding the following model

$$I = \frac{\sigma^{2.85}}{\lambda^{.413}\ (1-\rho)^{1.950}}. \qquad \text{Eq. 4.16}$$

The estimated values for a, b, and c, are -.413, -1.950, and 2.853 respectively. These values are somewhat consistent with the physical parameters of the problem. Specifically, the negative value for b suggests that delays decrease with $(1-\rho)$, while the positive values for c suggests that lock delay increases with standard deviation of service time. The negative value for a may seem to be inconsistent with physical properties of queuing by suggesting that delay *decreases* with volume. However, volume is also a component *of ρ. This result is also consistent in form to the* expression given for the delay of an m/g/1 queue, Eq. 4.13. As will be shown in other sections, the plot of the function is consistent in form to that shown in the exploratory data analysis.

Table 10 Estimation Results for Isolated Lock Model

Independent Variable	Coefficient	Std. Error
Log λ	-0.412905	0.091715
Log ρ_c	-1.947142	0.310564
Log σ_s	2.853188	0.084537

Figure 24 shows a plot of the observed values of y, log(I), versus the predicted values. The plot suggests an overall exceptional fit of the model to the data. The analysis of variance of the regression reveals that each of the model variables are highly significant in predicting delays at an isolated lock (Table 11). The R^2 of .963 also suggests a strong fit of the data, while the assumptions concerning the residuals appear to be valid.

In summary, either Equation 4.13 or 4.16 may serve as analytical model and metamodel respectively, for computing the delay at the first lock in an interdependent series of locks. Each of the models have their own set of advantages and disadvantages. The statistically estimated model, Equation 4.16, is based on the simulated data which may better represent the specific parameters associated with lock queuing, while the analytic model, Equation 4.13 has a theoretical foundation. Both functions, however, have the same variables and take on the same mathematical and graphical form. Either model may now be used in the coupling process described in the following section to expand the analysis from two locks to n locks. However, the statistically estimated model will be used for the remainder of the development of evaluation functions.

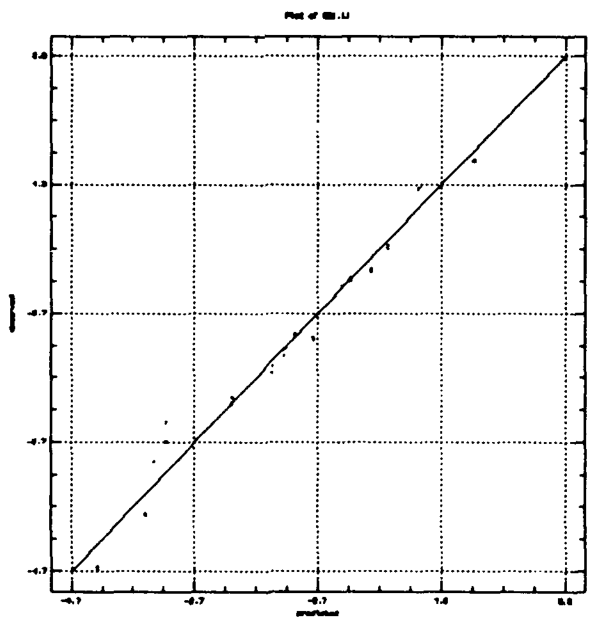

Figure 24 Observed versus Predicted Values for I

Table 11 Analysis of Variance for Isolated Lock Delay Model Calibration

Source	Sum of Squares	DF	Mean Sq.	F-Ratio
Log λ	2.2083	1	2.2083	27.77
Log ρ	38.9100	1	38.9100	489.31
Log σ	91.6092	1	91.6092	1152.03
Model	132.7270	3	44.2470	566.37
Error	2.3062	66	0.0795	

$R^2 = 0.963$

Technique for Coupling Locks

To illustrate the technique of using the model for the delay at an isolated lock and that of 2 interdependent locks, the three lock system in Figure 25 is used. The figure indicates that associated with each lock is a variance, utilization, arrival process, and departure process. Distance D_{12} separates Locks 1 and 2 while D_{23} separates Locks 2 and 3.

Note that Lock 1 has an independent arrival process, while the arrival processes at the remaining locks are related to the departure processes from the previous locks. Thus, the delay may be determined using either Equations 4.13 or 4.16. Enclosing Locks 1 and 2 in the figure is an effective lock, e2, which may act as a proxy for both Locks 1 and 2. Associated with Lock e2 is also a variance, utilization, arrival process, and departure process. The arrival process of Lock e2 is the same as that of Lock 1, while its departure process is the same as that of Lock 2.

Note that Locks e2 and 3 constitute a two lock system, i.e. the 2-lock model for the interdependence coefficient estimated directly from the simulation experiment may be applied. If ρ_{e2} and σ_{e2} are found, then the three lock system will be successfully converted to an equivalent two lock system. Because the arrival process for Lock e2 is independent, ρ_{e2} is the utilization that yields the total system delay for Locks 1 and 2, S_{12}, but as an independent

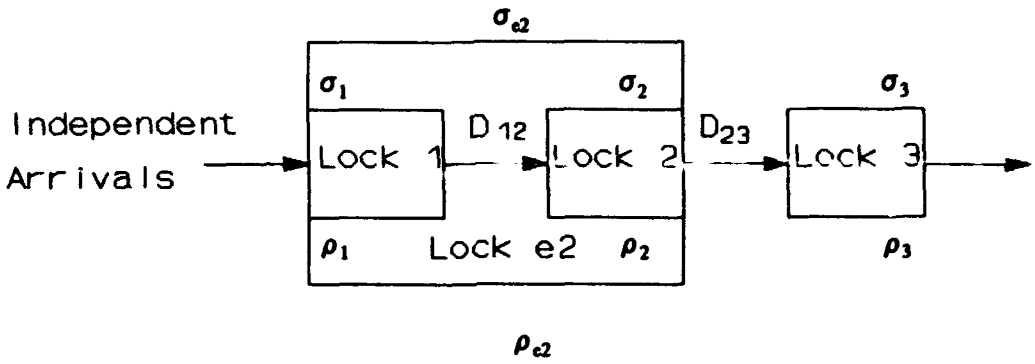

Figure 25 Conceptual System for Lock Coupling

lock. Therefore either Equations 4.13 or 4.16 may be applied to compute the delay for Lock e2, S_{e2}. First, using Eq. 4.16 we have

$$S_{e2} = \lambda^{a} \ (1-\rho_{e2})^{b} \ (\sigma_{e2})^{c} \qquad \text{Eq.4.17}$$

However, the delay for Lock e2, S_{e2}, is the same as the total system delay for Locks 1 and 2, S_{12}.

$$S_{e2} = S_{12} = 1 - \alpha \ \rho_c^{\beta} \ U^{\gamma} \ D^{\delta} = \lambda^{a} \ (1-\rho_{e2})^{b} \ (\sigma_{e2})^{c} \qquad \text{Eq. 4.18}$$

Next, an expression for the combined service time variance of Locks 1 and 2, $(\sigma_{e2})^2$ is obtained. If it is assumed that the service times of any group of n locks are independent, then the variances may be added linearly to yield the system variance, $(\sigma_{en})^2$.

$$\sigma^2_{en} = \sum_{i=1}^{n} \sigma^2_{i} \qquad \text{Eq. 4.19}$$

Therefore $(\sigma_{e2})^c$ may be replaced with $(\sigma_1^2 + \sigma_2^2)^{c/2}$ in Equation 4.18. The utilization of the effective lock, ρ_{e2} may now be solved directly from 4.18. Solving for ρ_{e2} we have

$$\rho_{e2} = 1 - (S_{12} \ \lambda^{-a} \ (\sigma_1^2 + \sigma_2^2)^{-c/2})^{1/b} \qquad \text{Eq. 4.20}$$

The interdependence coefficient may now be computed for a three lock system by adding the interdependence variable between Locks e2 and 3 to that of Locks 1 and 2, as illustrated in Figure 26. This is equivalent to replacing Y_{23} in Equation 4.12 with Y_{e3},

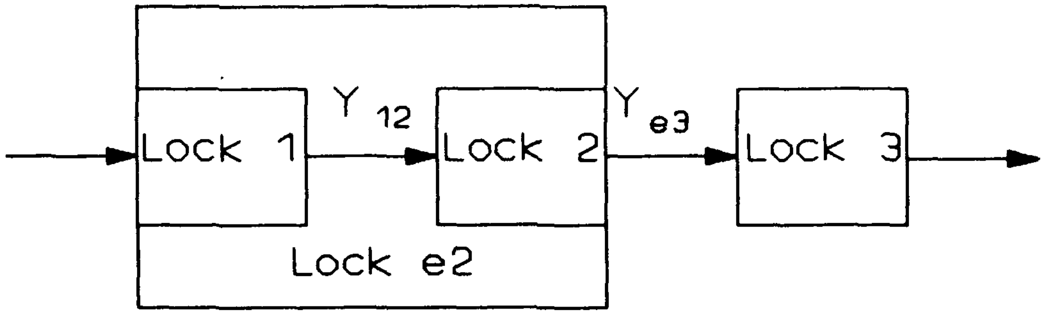

Figure 26 Adding Interdependence Variables for a 3 Lock System

$$(S/I)_3 = 1 - (Y_{12} + Y_{e3}) \quad \text{Eq. 4.21}$$

where

$$Y_{e3} = \alpha \max(\rho_{e2}, \rho_3)^{\beta} (U_{e3})^{\gamma} (D_{23})^{\delta} \quad \text{Eq. 4.22}$$

and

$$U_{e3} = \min(\rho_{e2}, \rho_3)/\max(\rho_{e2}, \rho_3). \quad \text{Eq. 4.23}$$

The coupling technique may now be applied in succession to yield the S/I for an N-lock system, $(S/I)_N$. This is done by first computing Y_N starting with $Y_2 = Y_{12}$. The following is an algorithmic expression for applying the technique in computing $(S/I)_N$.

<u>Step 1</u>
Begin with the two upstream most locks and compute the interdependence index between them.

$$Y_2 = \alpha \max(\rho_1, \rho_2)^{\beta} (U_{12})^{\gamma} (D_{12})^{\delta} \quad \text{Eq. 4.24}$$

Using Y_2, compute the interdependence coefficient for the first 2 locks.

$$(S/I)_2 = 1 - Y_2 \quad \text{Eq. 4.25}$$

Set n= 3.

<u>Step 2</u>
Compute the system delay for the first n-1 locks.

$$S_{n-1} = (S/I)_{n-1} \sum_{i=1}^{n-1} I_i \quad \text{Eq. 4.26}$$

Step 3
Compute the combined standard deviation of service time for the first n-1 locks.

$$\sigma_{cn} = \sum_{i=1}^{n-1} (\sigma_i^{2})^{1/2} \qquad \text{Eq. 4.27}$$

Step 4
Compute the effective utilization for the first n-1 locks.

$$\rho_{cn-1} = 1 - (S_{n-1} \lambda^{-a} (\sigma_{n-1})^{-c})^{1/b} \qquad \text{Eq. 4.28}$$

Step 5
Compute the interdependence index between Lock en-1 and Lock n.

$$Y_{cn} = \alpha \max(\rho_{cn-1}, \rho_n)^{\beta} (U_{cn})^{\gamma} (D_{n-1\,n})^{\delta} \qquad \text{Eq. 4.29}$$

Step 6
Compute the interdependence index for the n lock system.

$$Y_n = Y_{n-1} + Y_{cn} \qquad \text{Eq. 4.30}$$

Step 7
Compute the interdependence coefficient for the first n locks.

$$(S/I)_n = (S/I)_{n-1} - Y_n \qquad \text{Eq. 4.31}$$

If n=N, then stop, else increment n and go to step 2.

The above derivation for $(S/I)_n$ was performed using the statistically estimated formula for the delay at the first lock in the series, Equation 4.16. If an m/g/1 process is assumed for the first lock in the series, then ρ_{c2} is determined from Equation 4.13 where $W_{m/g/1}$ is replaced with S_{12}. The remaining steps in the technique are unchanged.

$$\rho_{c2} = .5(2 + 2\lambda S_{12}) - [(2 + 2\lambda S_{12})^2 + 4(\lambda^2(\sigma_{c2})^c - 2\lambda S)]^{1/2} \qquad \text{Eq. 4.29}$$

The results from the simulation experiment have now been expanded from incorporating systems with only two locks, to series with any number of locks. The expansion technique first assesses the interdependence of the first two locks estimated directly from the simulation results. Next, an additional factor of interdependence is added for the third lock. This additional factor is not based on the interdependence between Lock 3 and Lock 2 only, as Equation 4.12 would suggest, but rather is based on the interdependence between Lock 3 and the *system* composed of

Locks 1 and 2. In a similar manner, terms for interdependence associated with additional locks are added one at a time as suggested by the iterative nature of Equations 4.24 through 4.31.

Validation of Lock Coupling

The coupling of locks is performed to obtain an S/I ratio that reflects the interdependence within a system of more than two locks. The ratio is then used to calculate the total system delay among the locks. Therefore, the effectiveness of the coupling technique may be measured by the ability to yield values of system delay that are within acceptable deviations from simulated values.

To perform a test of the coupling technique, an experiment was conducted to provide simulated results for a three lock system. Comparisons of the total delay between the simulation model and the coupled meta-model provides some measure of effectiveness for coupling from a two lock system to a three lock system. Because the systems simulated were bidirectional, the experiment also provides an indirect validation of the one-directional assumption employed by the coupling technique.

The experiment involved three lock systems with the same utilization levels as the two lock simulation experiment, namely .890, .750, .660, and .320. A total of 40 three lock combinations with these utilizations were simulated. The simulations were conducted at a constant volume level of 30 tows/day and the capacities of the locks were adjusted accordingly to yield the desired utilizations. The distance between locks was 20 miles in all cases. A range of standard deviations of service time, σ_s, were considered by holding the coefficient of variation, σ/μ, constant at 0.5. As with the two lock simulation experiment, there were 30 runs per each of the 40 observations and approximately 1300 tows per run.

The table in Appendix 2 summarizes the numerical results of the experiment. Tabulated are 1) the average delay from simulation observed at each lock, 2) the variance of the service time at each lock, 3) the computed delay of each lock in isolation, 4) the level of interdependence as measured by the S/I ratio for each three lock system, 5) the computed total simulated delay, 6) the computed total delay, and 7) the percent deviation from simulation.

The average deviation from simulation is 10.06%. Although there does not appear to be a systematic bias in

the errors, the errors tend to be larger for systems involving lower utilizations. For example, the system with all three locks having a utilization of .320 has an error of 77.4%. However, systems consisting of low-utilization locks account for a significantly smaller amount of delay. This observation may be illustrated by computing the absolute value of the deviations for each system. The total of the absolute value of deviations for all systems is only 7.24% of the total simulated delay for all systems.

Observations Concerning Lock Interdependence

The generalized model for lock delay interdependence may now be utilized to explore the nature of lock interdependence which ultimately would reveal the impacts of interdependence on the benefits associated with lock capacity improvements. This may be done by 1) plotting the interdependence coefficient for different values of the relevant variables, e.g number of locks, distance, and capacity, and 2) performing a sensitivity analysis on the expressions for S/I.

First, a plot of S/I for both a two lock system and three lock system provides a first look at how the coefficient changes with an inclusion of an additional lock in the system In Figure 27, S/I is plotted versus volume for a two lock system with each lock having a capacity of 18 tows/day, a variance of 1.2, and distance of 20 miles. Also plotted are curves representing the inclusion of a third lock which is identical in every respect except that its capacity, is 18, 30, or 100. Note that the curves do not shift uniformly, but rather, the decrease in S/I associated with increasing the size of the cluster from two to three locks, increases with volume. Also, as the capacity of the third lock increases, the change in S/I associated with it decreases.

Next, the same system of two locks is plotted with curves representing three different three-lock systems in Figure 28. The three lock systems differ in their distance to the second lock which is 100, 20, or 5 miles, but are identical in all other respects. This plot reveals that the further away the third lock is from the two lock system, the smaller its contribution to the total interdependence. However, even very large distances, 100 miles, show some change in interdependence at very high utilizations.

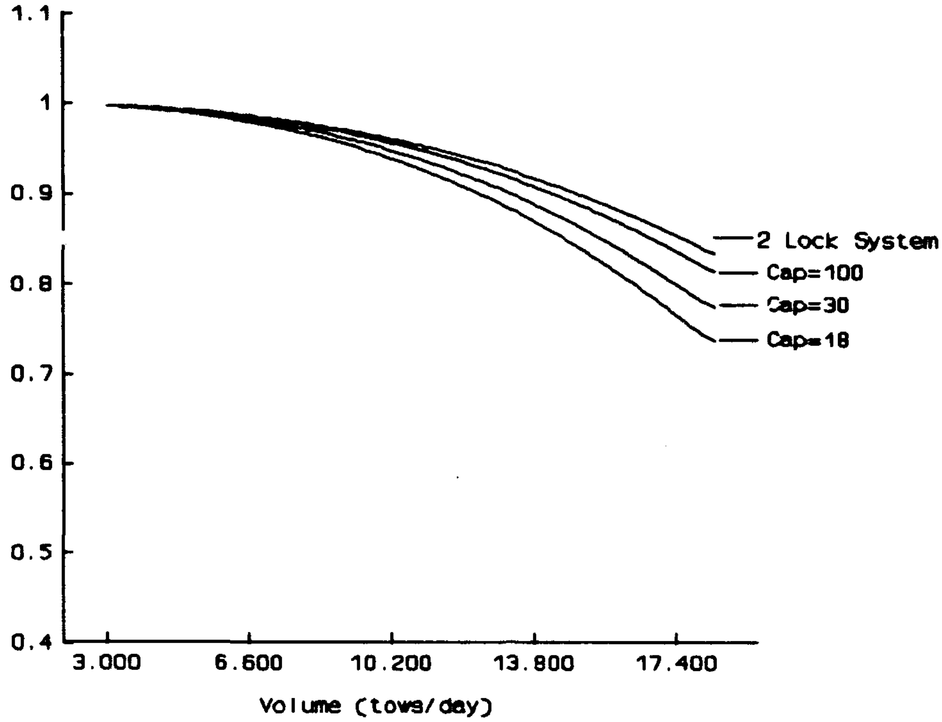

Figure 27 S/I for a 2 Lock and Various 3 Lock Systems

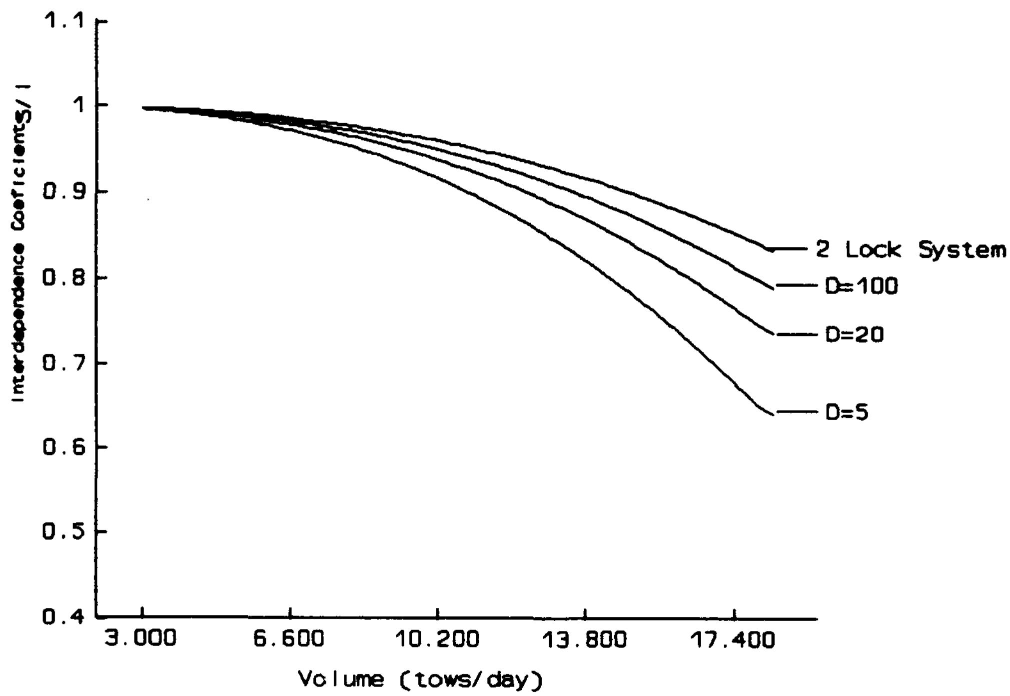

Figure 28 S/I for a 2 Lock and Various 3 Lock Systems

It is clear that the addition of a third lock reduces the value of S/I and the size of that reduction depends on the values of various lock and system variables. It would be helpful to know if the inclusion of additional (fourth, fifth, etc.) locks would yield the same size reduction as the addition of the third lock. Under purely deterministic conditions, the lower bound is 1/n, which is a series that decreases with n, but at a decreasing rate.

Although the model shows that S/I for the two lock system was greater than that of the deterministic case, 1/2, a reasonable hypothesis would be that the change in S/I due to increasing the system size, decreases. In other words, in a system of identical locks, equally spaced, the S/I curves would get closer together for larger system sizes. This hypothesis suggests that there is at least some practical limit where an additional lock does not significantly change the total interdependence in the system.

The hypothesis may be tested analytically by assuming a system of identical locks equally spaced. To prove the hypothesis true, it is necessary to show that in this system, the difference in $(S/I)_{k-1}$ and $(S/I)_k$ decreases with k. Using Equations 4.24 and 4.25, we have the following expression for this difference.

$$(S/I)_k - (S/I)_{k-1} = Y_{ck} = \alpha \max(\rho_{ck-1}, \rho_k)^{\beta} (U_{k-1\,k})^{\gamma} (D_{k-1\,k})^{\delta} \qquad \text{Eq. 4.32}$$

Because the system consists of equally spaced, identical locks, $\rho_1=\rho_2=\ldots=\rho$ and $D_{12}=D_{23}=\ldots=D$, Y_{ck} my be simplified. The maximum and minimum functions in Eq. 4.18 yield two possible expressions for Y_{ck}.

$$Y_{ck} = \alpha \ (\rho_{ck-1})^{\beta} \ (\rho/\rho_{ck-1})^{\gamma} \ D^{\delta} = \alpha \ (\rho_{ck-1})^{\beta-\gamma} \ \rho^{\gamma} \ D^{\delta}. \qquad \text{Eq. 4.33a}$$

$$Y_{ck} = \alpha \ \rho^{\beta} \ (\rho_{ck-1}/\rho)^{\gamma} \ D^{\delta} = \alpha \ (\rho_{ck-1})^{\gamma} \rho\beta-\gamma \ D^{\delta}. \qquad \text{Eq. 4.33b}$$

In order to determine if Y_{ck} decreases with k, it is only necessary to determine if ρ_{ck-1} decreases with k, noting that the model calibration shows $(\beta-\gamma)$ as positive. Removing the (k-1) subscript for estimation, from Equation 4.20 (the expression for I), we have the following expression for ρ_{ck-1}.

$$\rho_c = 1 - (S_c \ (\lambda)^{-a} \ (\sigma_c)^{-2c})^{1/b} \qquad \text{Eq. 4.34}$$

As the number of locks in the system, k, increases, both the total system delay, S_{ck-1} and standard deviation of service time, σ_{ck-1} increase. By computing $\partial\rho_c/\partial S$ and $\partial\rho_c/\partial\sigma$, the effects of S and σ on ρ_c may be determined.

$$\frac{\partial \rho}{\partial S} = \frac{1}{b} \left(S_e \lambda^{-a} \sigma_e^{-c}\right)^{1/b-1} \left(\lambda^{-a} \sigma_e^{-c}\right)$$

$$= \frac{\lambda^{-a} \sigma_e^{-c}}{b} \left(S_e \lambda^{-a} \sigma_e^{-c}\right)^{1/b-1} \qquad \text{Eq. 4.35}$$

$$\frac{\partial \rho}{\partial \sigma} = \frac{c}{b} \left(S_e \lambda^{-a} \sigma_e^{-c}\right)^{1/b-1} \left(S_e \lambda^{-a} \sigma^{-c-1}\right) \qquad \text{Eq. 4.36}$$

For $b<0$, $\partial\rho/\partial S$ is positive while $\partial\rho/\partial\sigma$ is negative. It cannot be concluded a priori which term is greater. Therefore, the hypothesis of decreasing shifts in S/I is not necessarily true. The signs of the derivatives suggest that there are two forces at work on Y_{ck}, namely the system waiting time S and service time variance σ^2. As system waiting time increases, the change in S/I, Y_{ck}, tends to increase as identical locks are added to the system. On the other hand, Y_{ck} tends to decrease as the service time variance increases. Thus, for sufficiently high values of service time variance, the hypothesis of decreasing changes in S/I may hold true, suggesting a possible limit in cluster size. In general, however, another method of determining cluster size is needed. An alternative method is provided earlier in this Chapter.

Numerical Example of Evaluation Functions

The objective of the simulation experiment and subsequent analysis has been to establish a workable functional relationship for the average waiting time of tows through a system of n interdependent locks, S_n. The expression obtained is that of a set of iterative functions for computing S_2 through S_n. In Chapter 3 it was shown that once the average interdependent delay is formulated, a function may be developed for the evaluation of a combination of proposed projects. In this section, such a function is developed and a numerical example provided for illustration.

The measure of effectiveness for the system evaluation is that of total system cost associated with given levels of output (tows per day). The system cost varies with the implementation of a combination of capacity improvement projects as specified by the set of projects, P. Implementation of a project effectively increases the capacity of the locks included in P as well as an associated

capital cost. Assuming time periods of one half year, the total system cost (TSC) for a given P for a given time period is the sum of the delay costs and the capital costs,

$$TSC_{tP} = \lambda_t \; S_{aP} \; O_W \quad (1+r/2)^{2t} + \sum_{i \in P} K_i \qquad \text{Eq. 4.37}$$

where O_W is the average opportunity cost of delay for tows, r is the annual interest rate, K_i is the capital cost of project i times (u/p,r/2,h) (the capital recovery factor for a planning horizon of h time periods). Note that a demand function relating the volume level to time must be specified. The implementation of a combination of projects P, reduces the total amount of delay experienced in the system.

Consider a system of four locks, each with a proposed capacity expansion as defined in Table 12. The implementation of a project at a given lock would increase the capacity from the current level to the proposed level at the capital cost indicated. In this example, the opportunity cost of delay is assumed to be $500/tow-hour while the standard deviation of service time is 0.5 for all locks and an interest rate of 2 percent. The capital costs are spread uniformly over a planning horizon of 50 years.

In addition to these assumed values, a congestion tolerance factor of 0.9 and a linear demand are assumed. The congestion tolerance factor is the utilization beyond which traffic will divert to another transport modes. When

Table 12 Parameters for Locks in Illustrative Example

	Lock 1	Lock 2	Lock 3	Lock 4
Current Capacity	15	20	25	30
Improved Capacity	40	40	40	40
Capital Cost	400	325	200	200
Distance		20	20	20

the congestion tolerance is not exceeded the demand function in this is simply

$$\lambda_t = 7.7 + 0.6\ t. \qquad \text{Eq. 4.38}$$

Under these assumptions, the equation for the total system cost for combination set P={1,2} in period 10 would be

$$TSC_{10,P} = 5.0\ S_{10,P}\ (500)(182.625)\ (1.01)^{20} + (725)(.013) \qquad \text{Eq. 4.39}$$

Table 13 shows the results from computing the average delays for the system of locks without the implementation of any improvements. Included are the average delays for both interdependent, S4, and independent, I4, conditions. The observations extend to 9.5 years whereupon the congestion tolerance is exceeded. The difference in average delay between independent and interdependent conditions, Δ, ranges disproportionally from 5.5 percent at a volume of 8.0 tows per day to 20.8 percent at 13.4 tows per day.

The results shown in Table 14 are for the same system if all four improvement projects were to be implemented immediately. Like Table 13, Table 14 includes the average delay in the system for both interdependent and

Table 13 Comparative Delays (No Projects Implemented)

Time	Volume	λ_1	λ_2	λ_3	λ_4	(S/I)4	S4	I4	% Δ
0.5	8.0	0.533	0.400	0.320	0.267	0.948	5.98	6.32	5.5
1.0	8.3	0.553	0.415	0.332	0.277	0.943	6.41	6.79	6.0
1.5	8.6	0.573	0.430	0.344	0.287	0.938	6.87	7.32	6.6
2.0	8.9	0.593	0.445	0.356	0.297	0.933	7.38	7.91	7.1
2.5	9.2	0.613	0.460	0.368	0.307	0.928	7.96	8.57	7.7
3.0	9.5	0.633	0.475	0.380	0.317	0.923	8.60	9.32	8.3
3.5	9.8	0.653	0.490	0.392	0.327	0.917	9.33	10.17	9.0
4.0	10.1	0.673	0.505	0.404	0.337	0.912	10.17	11.15	9.7
4.5	10.4	0.693	0.520	0.416	0.347	0.905	11.13	12.29	10.4
5.0	10.7	0.713	0.535	0.428	0.357	0.899	12.26	13.64	11.2
5.5	11.0	0.733	0.550	0.440	0.367	0.892	13.60	15.24	12.0
6.0	11.3	0.753	0.565	0.452	0.377	0.886	15.22	17.18	12.9
6.5	11.6	0.773	0.580	0.464	0.387	0.878	17.20	19.58	13.8
7.0	11.9	0.793	0.595	0.476	0.397	0.871	19.69	22.61	14.8
7.5	12.2	0.813	0.610	0.488	0.407	0.863	22.91	26.54	15.9
8.0	12.5	0.833	0.625	0.500	0.417	0.855	27.19	31.81	17.0
8.5	12.8	0.853	0.640	0.512	0.427	0.846	33.14	39.16	18.2
9.0	13.1	0.873	0.655	0.524	0.437	0.837	41.83	49.95	19.4
9.5	13.4	0.893	0.670	0.536	0.447	0.828	55.43	66.94	20.8

Table 14 Comparative Delays (All Projects Implemented)

Time	Volume	λ_1	λ_2	λ_3	λ_4	(S/I)4	S4	I4	% Δ
1.0	8.3	0.208	0.208	0.208	0.208	0.986	3.591	3.643	1.5
2.0	8.9	0.223	0.223	0.223	0.223	0.984	3.828	3.892	1.7
3.0	9.5	0.238	0.238	0.238	0.238	0.981	4.076	4.153	1.9
4.0	10.1	0.253	0.253	0.253	0.253	0.979	4.335	4.428	2.2
5.0	10.7	0.268	0.268	0.268	0.268	0.976	4.606	4.717	2.4
6.0	11.3	0.283	0.283	0.283	0.283	0.974	4.892	5.024	2.7
7.0	11.9	0.298	0.298	0.298	0.298	0.971	5.192	5.348	3.0
8.0	12.5	0.313	0.313	0.313	0.313	0.968	5.510	5.692	3.3
9.0	13.1	0.328	0.328	0.328	0.328	0.965	5.846	6.059	3.6
10.0	13.7	0.343	0.343	0.343	0.343	0.962	6.201	6.449	4.0
11.0	14.3	0.358	0.358	0.358	0.358	0.958	6.579	6.867	4.4
12.0	14.9	0.373	0.373	0.373	0.373	0.955	6.981	7.314	4.8
13.0	15.5	0.388	0.388	0.388	0.388	0.951	7.410	7.793	5.2
14.0	16.1	0.403	0.403	0.403	0.403	0.947	7.868	8.308	5.6
15.0	16.7	0.418	0.418	0.418	0.418	0.943	8.358	8.863	6.1
16.0	17.3	0.433	0.433	0.433	0.433	0.939	8.883	9.463	6.5
17.0	17.9	0.448	0.448	0.448	0.448	0.934	9.448	10.112	7.0
18.0	18.5	0.463	0.463	0.463	0.463	0.930	10.057	10.816	7.5
19.0	19.1	0.478	0.478	0.478	0.478	0.925	10.715	11.581	8.1
20.0	19.7	0.493	0.493	0.493	0.493	0.920	11.427	12.415	8.7
21.0	20.3	0.508	0.508	0.508	0.508	0.915	12.200	13.328	9.2
22.0	20.9	0.523	0.523	0.523	0.523	0.910	13.041	14.328	9.9
23.0	21.5	0.538	0.538	0.538	0.538	0.905	13.959	15.427	10.5
24.0	22.1	0.553	0.553	0.553	0.553	0.899	14.965	16.639	11.2
25.0	22.7	0.568	0.568	0.568	0.568	0.894	16.069	17.981	11.9
26.0	23.3	0.583	0.583	0.583	0.583	0.888	17.287	19.471	12.6

interdependent conditions. Because capacities are higher in the improved system, the effects of interdependence as expressed by the difference with the independent case are smaller for the same volume level. For example, at a volume of 11.0 tows per day the difference is 12 percent with no projects implemented and only 2.6 percent upon the implementation of all four projects.

Thus far only two of the 16 possible combinations of project implementations have been examined. To examine the relationships among the costs associated with the remaining implementation combinations, the combination set is divided into three different groups. The grouping of projects is for clarity of interpretation and not a part of the sequencing routine. The first group includes those combinations involving one project, the second group two projects, and the third three projects. Figures 29 through 31 are plots of the total system cost over time for each of these three groups.

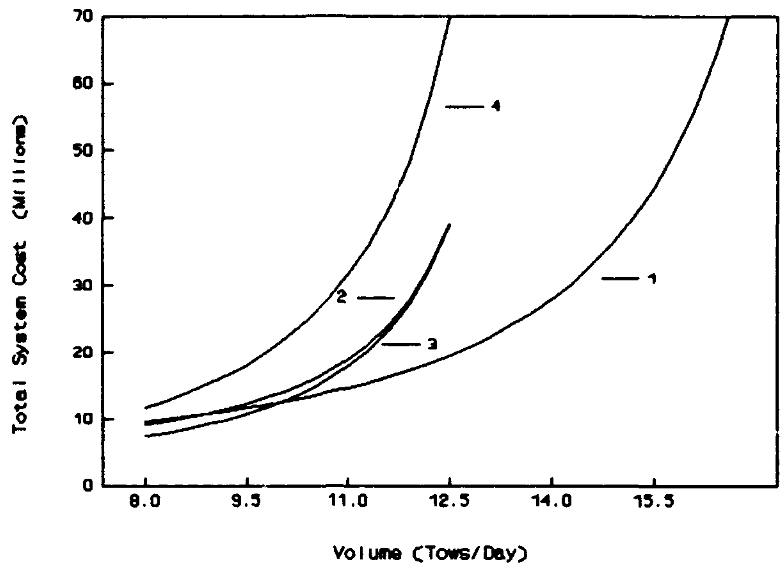

Figure 29 Plots of Combinations Involving One Project

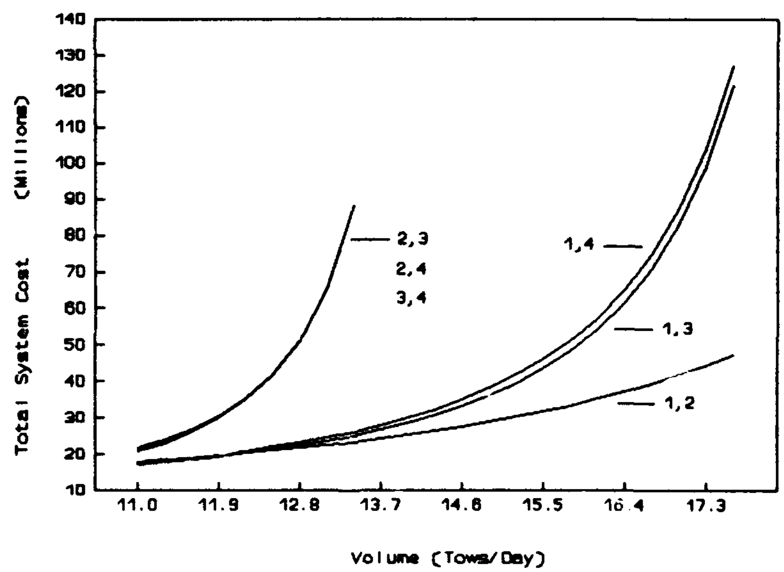

Figure 30 Plots of Combinations Involving Two Projects

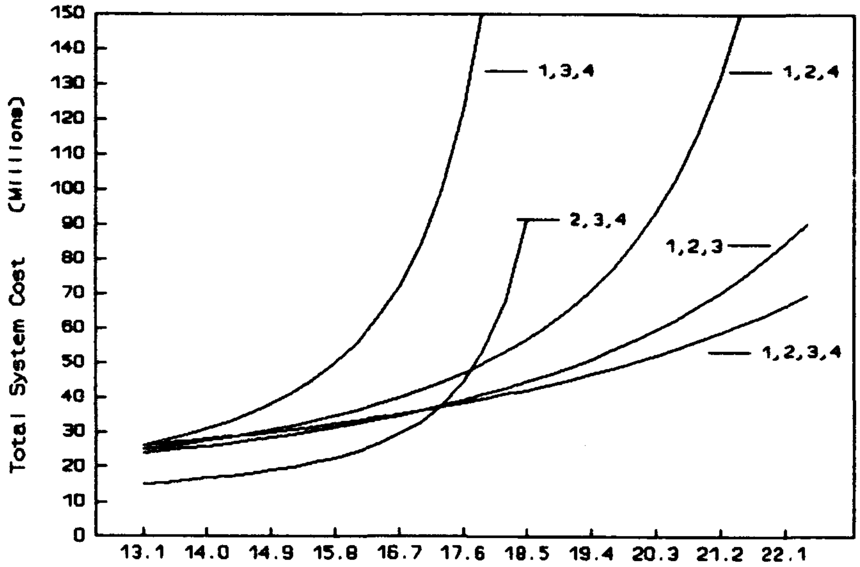

Figure 31 Plots of Combinations Involving Three Projects

In Figure 29 the combinations involving one project are plotted. While the cost under Project 3 is lowest for low volumes, Project 1 appears to have the minimum system cost throughout most all volume levels (and time periods). The two project combinations are plotted in Figure 31. Here, Combination 1,2 yields the minimum total system cost for nearly all volume levels shown.

In addition to combinations involving three projects, Figure 31 also includes combination 1,2,3,4, the only combination involving four projects. Combination 1,2,3 is next in the expansion sequence. Finally, at a volume of 17.2, combination 1,2,3,4, the implementation of all projects, becomes the minimum cost combination.

The minimum-cost combinations in each of these groups may be superimposed to establish an expansion path that begins with the implementation of Project 1 and ends with the implementation of Project 4. This expansion path is shown graphically in Figure 32 in which the sequence and schedule may be read directly (ignoring budget constraints). The first project to be implemented is Project 1, which may be started immediately since {compare to null alt.}. At a volume of 13.4 (t = 9.5 years), the costs associated with doing both Projects 1 and 2 are lower than that of Project 1 only. Therefore, after 9.5 years, the second project is to be implemented. Continuing in this manner, Project 3 should begin in year 11.5 and Project 4 in year 17.

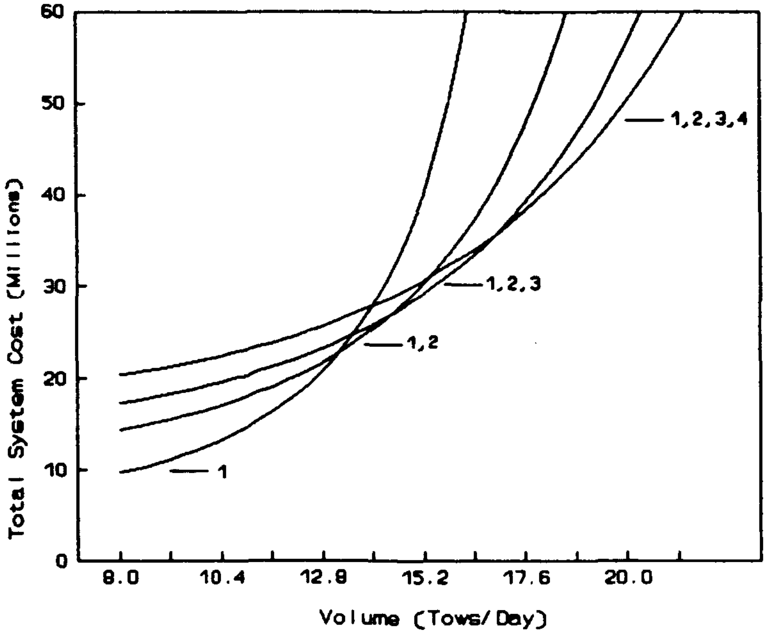

Figure 32 Plot of Expansion Path for Numerical Example

This same expansion path is tabulated in Table 15 which includes the numerical values of minimum system costs over the path. A similar table is produced for the case of independent locks in Table 16. In this example, the project sequence is identical for both the interdependent and independent cases. However, the values for the system costs are noticeably lower for the interdependent case. Also, the start dates for additional projects are about one half year later in the interdependent case. This is because system costs increase at a slightly lower rate for interdependent locks.

Table 15 System Costs for Interdependent Expansion Path

Time	Volume	Null	1	1,2	1,2,3	1,2,3,4
1.0	8.3	4,952,059				
2.0	8.9	6,243,604				
3.0	9.5	7,919,970				
4.0	10.1	10,152,997				
5.0	10.7		13,969,383			
6.0	11.3		15,476,647			
7.0	11.9		17,302,820			
8.0	12.5		19,538,891			
8.5	12.8		20,848,754			
9.0	13.1		22,313,055			
9.5	13.4			23,423,970		
10.0	13.7			24,352,819		
10.5	14.0			25,356,646		
11.0	14.3			26,442,959		
11.5	14.6				27,441,356	
12.0	14.9				28,297,701	
13.0	15.5				30,181,571	
14.0	16.1				32,323,418	
14.5	16.4				33,503,880	
15.0	16.7				34,765,224	
15.5	17.0					36,055,966
16.0	17.3					37,143,570
17.0	17.9					39,509,491
18.0	18.5					42,157,134
19.0	19.1					45,123,864
20,0	19.7					48,452,965
21.0	20.3					52,194,759
22.0	20.9					56,407,996
23.0	21.5					61,161,551
24.0	22.1					66,536,551
25.0	22.7					72,629,012
26.0	23.3					79,553,182

The system cost for each time period (one half year) of the planning horizon defines a cash flow which may be discounted and compared for the interdependent and independent cases. The net present values of the system costs along the expansion path for the first 26.5 years are 1,324,094,320 and 1,395,372,157 for the interdependent and independent cases, respectively. For the years 0 through 26.5, the total discounted system costs are about 5.4% higher for the independent case. This difference increases to 26.4% when the entire 50 year planning horizon is considered.

From the analysis of this example, it appears that interdependence may have a significant effect on the *magnitude* of the system costs, and a noticeable effect on the start times of projects. The sequence of projects appears to be affected very little by interdependence. The impacts of interdependence on the sequencing and scheduling methodology are discussed in Chapter 5.

Table 16 System Costs for Independent Expansion Path

Time	Volume	Null	1	1,2	1,2,3	1,2,3,4
1.0	8.3	5,250,915				
2.0	8.9	6,688,454				
3.0	9.5	8,580,735				
4.0	10.1	11,138,173				
5.0	10.7		14,407,910			
6.0	11.3		16,072,019			
7.0	11.9		18,108,908			
8.0	12.5		20,629,571			
8.5	12.8		22,118,037			
9.0	13.1			23,150,332		
9.5	13.4			24,089,042		
10.0	13.7			25,105,888		
10.5	14.0			26,208,786		
11.0	14.3			27,208,800		
11.5	14.6			28,078,597		
12.0	14.9			29,007,070		
13.0	15.5			31,058,479		
14.0	16.1			33,404,443		
14.5	16.4			34,703,112		
15.0	16.7				36,066,565	
15.5	17.0				37,200,404	
16.0	17.3				38,402,585	
17.0	17.9				41,030,316	
18.0	18.5				43,990,059	
19.0	19.1				47,328,644	
20.0	19.7				51,100,685	
21.0	20.3				55,370,114	
22.0	20.9				60,212,067	
23.0	21.5				65,715,231	
24.0	22.1				71,984,757	
25.0	22.7				79,145,936	
26.0	23.3				87,348,824	

Summary

In this chapter, the results of simulation for both the system and isolated cases as well as S/I have been presented. It has been shown that the model of the factor variables for S/I adequately fits the data obtained from the simulation model. The metamodel was expanded to a system of iterative equations to incorporate systems of more than two locks. A validation of the lock coupling technique showed that the deviation from simulation for three lock systems averaged 10.1% for systems involving utilizations ranging from .320 to .890.

Using the metamodel for S/I, some observations concerning lock interdependence were made. It was found that the interdependence of the system increases with system size. The size of the increase depends on various lock

characteristics. A sensitivity analysis revealed that the amount of interdependence in a system does not necessarily converge. Therefore, a method of identifying division points in lock systems (or clustering) is necessary.

A numerical example involving four hypothetical projects was shown as an illustration of the resulting evaluation method. There was no difference in the sequence of the projects between the independent and interdependent case. However the start times of projects were slightly delayed due to interdependence. More significantly, the present value of the system costs for the optimal expansion path over the planning horizon was 26.4% lower for the interdependent case.

CHAPTER 5
SEQUENCING AND SCHEDULING INTERDEPENDENT LOCK IMPROVEMENTS

In this chapter the methodology presented in Chapter 3 for sequencing and scheduling interdependent lock improvements projects is implemented. The methodology involves using the system cost functions developed in Chapter 4 to evaluate various combinations of lock improvements in such a way as to establish a minimum cost expansion path over time. In the following section, it is shown that the functions obtained are consistent with those illustrated in Chapter 3. Next, the effects of interdependence on the system cost curves is discussed and a method of subdividing a series of projects into mutually independent clusters is described. Finally, the solution technique for selecting the minimum cost expansion path is formalized and illustrated on the proposed expansion projects of a particular waterway segment.

Properties of System Cost Functions

The proposed sequencing methodology was to superimpose curves representing the total cost of a system of locks under the implementation of a given combination of improvements. It was hypothesized that the resulting functions would have the properties necessary to define a sequential expansion path based on the lower "envelope" of combinations. More specifically, the method as illustrated in Chapter 3 uses cost functions that are monotonically increasing with, at most, one intersection between any two curves. Given these requirements, two desirable properties are a positive first derivative and positive second derivative with respect to λ, for all values of λ greater than zero. Although, the four lock numerical example in Chapter 4 suggests that the cost curves behave like those shown in Chapter 3, more general evidence is helpful.

By differentiating a form of the total system cost (TSC) function derived in Chapter 4, and knowing the values of the estimated parameters, it should be possible to establish whether the expression is positive or negative. Repeating Eq. 4.34 while expanding S_{nP} we have

$$TSC_P = \lambda \sum_{i=1}^{n} I_i(\lambda)\ (O_w)\ (1 + r/2)^t\ (S/I)_n + \sum_{i \in P} k_i \qquad \text{Eq. 5.1}$$

In showing that the first and second derivatives of this function are positive, it is only necessary to show that they are positive for the expression given by Eq. 5.2. That

is, if the first and second derivatives are positive for I_i, they will be positive for ΣI_i.

$$f(\lambda) = \lambda \; I(\lambda) \; (S/I)_a. \qquad \text{Eq. 5.2}$$

Also, $(S/I)_2$ is of the same form as $(S/I)_a$ and therefore may be substituted in Eq. 5.2 for purposes of differentiating. Before differentiating, it is necessary to expand $(S/I)_2$ to be a function of λ. In expanding $(S/I)_2$, Lock 1 will be specified as the having the greater ρ. This may be done without loss of generality.

$$(S/I)_2 = 1 - \alpha \; (\rho_1)^{\beta} \; (U_{12})^{\gamma} \; (D_{12}) \qquad \text{Eq. 5.3a}$$
$$= 1 - \alpha \; \lambda^{\beta} \; (\mu_2)^{\gamma} \; (\mu_1)^{\beta-\gamma} \; (D_{12}) \qquad \text{Eq. 5.3b}$$
$$= 1 - \kappa \; \lambda^{\beta} \qquad \text{Eq. 5.3c}$$

where $\kappa = \alpha \; (\mu_2)^{\gamma} \; (\mu_1)^{\beta-\gamma} \; (D_{12})$.

After substituting, the function to differentiate becomes

$$f(\lambda) = \sigma^c \lambda^{a+1} (1 - \lambda/\mu_1)^b \; (1 - \kappa\lambda^{\beta}) \qquad \text{Eq. 5.4}$$

Differentiating, we have

$$\frac{df(\lambda)}{d\lambda} = (a+1)\sigma^c\lambda^a(1 - \lambda/\mu)^b - \sigma^c\lambda^{a+1}b/\mu(1 - \lambda/\mu)^{b-1}$$
$$- (a + \beta + 1)\sigma^c\kappa\lambda^{a+\beta}(1 - \lambda/\mu)^b - \sigma^c\kappa\lambda^{a+\beta+1} \; b(1 - \lambda/\mu)^{b-1} \qquad \text{Eq. 5.5}$$

The first derivative consists of four terms, of which only one, the third, is negative for b<0. With the knowledge that the calibrated values for a and β are -0.413 and 2.455, respectively, the fourth term alone is shown to be larger in absolute value than the only negative term for $\lambda>0$. Therefore, the first derivative for the system cost function is positive, meaning that the curve is always increasing.

Appendix 2 provides the resulting expression for the second derivative and shows that it is also positive for all $\lambda>0$. The positive second derivative implies that the cost curves increase at an increasing rate.

An additional property of the cost functions is that they are asymptotic to the minimum capacity in the series, or system bottleneck. Because the implementation of projects provides an expansion in lock capacity, the minimum capacity may vary from combination to combination. This asymptotic property may be shown by taking the limit of the cost function as λ approaches μ_{min}.

$$\lim_{\lambda \to \mu_{min}} TSC(\lambda) = \lim_{\lambda \to \mu_{min}} \frac{\lambda^{a+1}}{(1-\lambda/\mu_{min})^{b}} = \infty \qquad \text{Eq. 5.6}$$

In general the combinations involving more numerous projects have a greater value of minimum capacity, allowing them to avoid steeply escalating costs until later periods.

As a final observation, only if the current traffic volume in the system is zero will the vertical intercept of the cost function equal the capital cost of the combination. Therefore the actual intercept is somewhat higher than K_P since $\lambda_0 > 0$.

It has been shown that the first and second derivatives of the system cost functions are positive and that they are asymptotic to μ_{min}. Given these properties, some conclusions may also be made concerning the number of intersections between two combination curves, A and B. First, if $K_A \geq K_B$ and $(\mu_{min})_A \leq (\mu_{min})_B$, then the two curves have either no intersections or two intersections for $\lambda > 0$, and second, if $K_A \geq K_B$ and $(\mu_{min})_A \geq (\mu_{min})_B$, then the curves have exactly one intersection for $\lambda > 0$.

Figure 33 illustrates the properties of the system cost curves derived in this section for two combinations A and B. Because the first and second derivatives are always positive, both curves are shown to increase at an increasing rate. Because current volume levels are greater than zero, the vertical intercepts are not K_A and K_B. Curves A and B are shown asymptotic to the minimum capacity that exists following the implementation of the projects in the combination.

The slope, intercept, and asymptotic properties of the system cost curves have been shown to be consistent with those assumed when the sequencing and scheduling methodology was developed in Chapter 3. In the following section, these properties are extended to provide some insight on the effects of interdependence on the magnitude of costs as well as the sequence and schedule of projects.

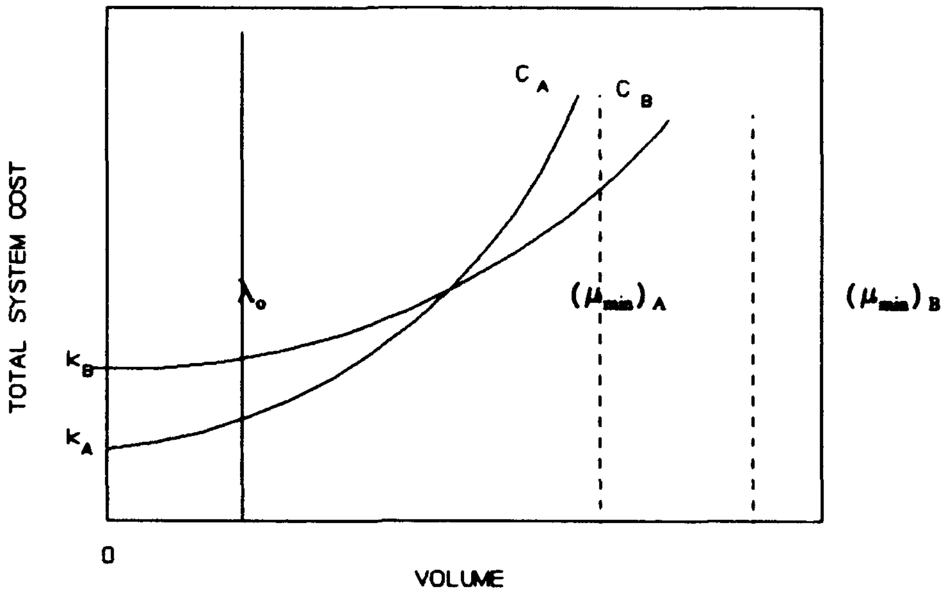

Figure 33 Illustration of System Cost Curve Properties

Effects of Interdependence

In Chapter 4 a numerical example showed that the magnitude of the total costs for a system of locks was lower when interdependence effects were included. This is because the system delay is always lower than the isolated delay. Also, the expression for the total costs, Eq. 5.1, reveals that interdependence only affects the first term, i.e. the capital costs of a combination of projects have no bearing on the shifts in the system cost curves due to interdependence. The effects of interdependence may be expressed by expanding the equation for delay costs.

$$(\text{Delay Cost})_P = (O_w)(1 + r/2)^t \sum_{i=1}^{n} Ii \ (S/I)_n \qquad \text{Eq. 5.7}$$

$$= (O_w)(1 + r/2)^t \sum_{i=1}^{n} I_i \ (1 - Y_n) \qquad \text{Eq. 5.8}$$

$$= (O_w)(1 + r/2)^t \sum_{i=1}^{n} I_i$$

$$- (O_w)(1 + r/2)^t \sum_{i=1}^{n} I_i \, Y_n \qquad \text{Eq. 5.9}$$

Note that the first term in Eq. 5.9 is the delay under independent conditions while the second term represents a shift in the cost curve due to interdependence. While the shift is always downward, it is never uniform. This is because Y_n and I_i both increase nonlinearly with λ.

Since the cost curves for all combinations would all have a downward shift from independence to interdependence, the expansion path will always have a decrease in the magnitude of the total system costs and therefore in the net present value and benefit-cost ratio of the rehabilitation program. If shifts for all combinations were identical there would be absolutely no change in either the sequence or schedule of projects. Although all shifts are downward, the possibility exists that the sequence and/or schedule will be different for the interdependent case.

The basic properties of the system cost functions are not affected by interdependence. That is, the first and second derivatives are still positive, and the curves are still asymptotic to μ_{min}. In exploring the possible change from independence in the sequence and schedule of projects, three cases of geometric orientation of cost curves are considered. The three cases cover all possible ways in which one project may precede another in the implementation sequence.

In these examples, SC_{oP} refers to the system costs assuming independence and SC_P assuming interdependence. In each case, a set of projects to be implemented, P, may be expanded either to $P \cup i$ or $P \cup j$. The implementation set is then further expanded to $P \cup i \cup j$. Without loss of generality, it will be assumed that in each case Combination $P \cup i$ is preferred to Combination $P \cup j$ on the expansion path. In other words, the cost minimizing sequence following P is first i, then j. The issue in each case is, what will have to occur in order for the shifts in cost curves to result in a change in this expansion path.

Case 1

The first case is where the curve for Combination PUj lies completely above that of PUi in the independent case. Here, there is no expansion conflict present such as discussed in Chapter 3, and it can be said a priori that Project i should precede Project j in the expansion sequence. In order for this situation to occur, K_{PUj} must be $\geq K_{PUi}$ and $(\mu_{min})_{PUj}$ must be $\geq (\mu_{min})_{PUi}$. This case is shown graphically in Figure 34.

Interdependence effects will cause a downward shift in all the curves including those for PUi and PUj. A possibility that the sequence is changed by such shifts exists only if SC_{oPUi} and SC_{oPUj} shift to the extent that SC_{PUi} and SC_{PUj} intersect. This can only occur if the shift in SC_{oPUj}, Δ_{PUj}, is sufficiently larger than the shift in SC_{oPUi}, Δ_{PUi}. Because μ_{min} and the magnitude of delays are greater for PUj than for PUi, Δ_{PUj} is likely to be greater than Δ_{PUi}.

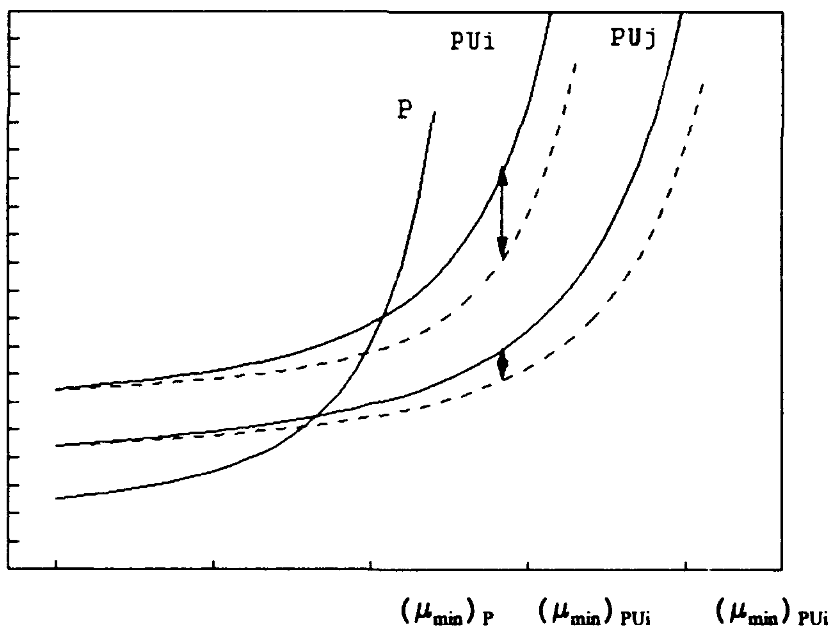

Figure 34 Illustration of Case 1

However, this condition only introduces the *possibility* that interdependence will affect the sequence. Explicitly, the condition for this possibility is

$$(\Delta_{P\cup j} - \Delta_{P\cup i}) > (SC_{oP\cup j} - SC_{oP\cup i}) . \qquad \text{Eq. 5.10}$$

Expanding the left side of Eq. 5.10 we have

$$C_{oP\cup j} - C_{oP\cup j} = \left(\sum_{i=1}^{n} I_i\right)_{P\cup j} + K_{P\cup j} - \left(\sum_{i=1}^{n} I_i\right)_{P\cup i} + K_{P\cup j} \qquad \text{Eq. 5.11}$$

$$= \left[\left(\sum_{i=1}^{n} I_i\right)_{P\cup j} - \left(\sum_{i=1}^{n} I_i\right)_{P\cup i}\right] - (K_{P\cup j} - K_{P\cup i}) \qquad \text{Eq. 5.12}$$

From Eq. 5.12, it can be seen that $(K_{P\cup j} - K_{P\cup i})$ is an absolute lower bound on $(SC_{oP\cup j} - SC_{oP\cup i})$. From this lower bound, a minimum criterion may be established for the possibility of a change in the expansion sequence. For example if the ratio of $K_{P\cup i}$ to $K_{P\cup j}$ is less than some specified lower bound on the value for (S/I), then the interdependence can be assumed to have no effect on the sequence for that step of the analysis.

Case 2

The second and third cases are unlike the first in that they represent the occurrence of an expansion conflict. In Chapter 3 it was shown that in such cases, it is necessary to compare two areas formed by intersections of the cost curves. Case 2 is illustrated in Figure 35. It shows that if projects are independent, Combination P∪i should precede Combination P∪j, because Area 1 is noticeably greater than Area 2. The case illustrated in Figure 35 is only possible if $(\mu_{min})_{P\cup j} \geq (\mu_{min})_{P\cup i}$ and $K_{P\cup j} \geq K_{P\cup i}$.

As with Case 1, the effects of interdependence will shift all curves downward, including $SC_{oP\cup i}$ and $SC_{oP\cup j}$. Note that a shift that would tend to increase Area 1 and/or decrease Area 2, tends to preserve the current sequence, while shifts that tend to decrease Area 1 and/or increase Area 2 favor a swap of Project i and Project j in the sequence. The shift in SC_{oP} tends to decrease Area 1 (potentially changing the sequence) and $SC_{oP\cup i\cup j}$ tends to

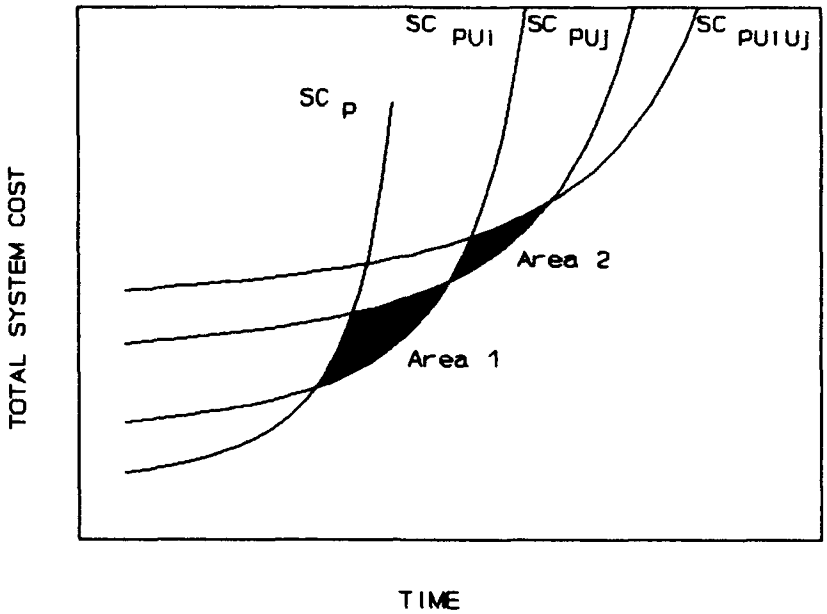

Figure 35 Illustration of Case 2

decrease Area 2 (potentially preserving the sequence). The shift in SC_{oPUi} tends to cause some increase in Area 1 and some decrease in Area 2, which tends to preserve the sequence. The shift in SC_{oPUj} has the opposite effect on the areas as SC_{oPUi}, favoring a swap in the sequence.

Case 3

The final case is similar to the second. However, the preferred combination, PUi, is more costly than PUj in early time periods and less costly in later time periods. The case is illustrated in Figure 36. For this case to occur, $(\mu_{min})_{PUj}$ must be ≤ $(\mu_{min})_{PUi}$ and K_{PUj} must be ≤ K_{PUi}. In this case, Area 2 is greater than Area 1. Thus, Project i should precede Project j in the expansion path.

The effects of interdependence are similar, but reversed from Case 2. The shifts that tend to increase Area 2 and/or decrease Area 1, tend to preserve the current sequence, while shifts that tend to decrease Area 2 and/or increase Area 1 favor a swap in the sequence of Project i and Project j. The shift in SC_{oPUiUj} tends to decrease Area 2 (potentially changing the sequence) and SC_{oP} tends to decrease Area 1 (potentially preserving the sequence. The shift in SC_{oPUi} tends to cause some increase in Area 2 and

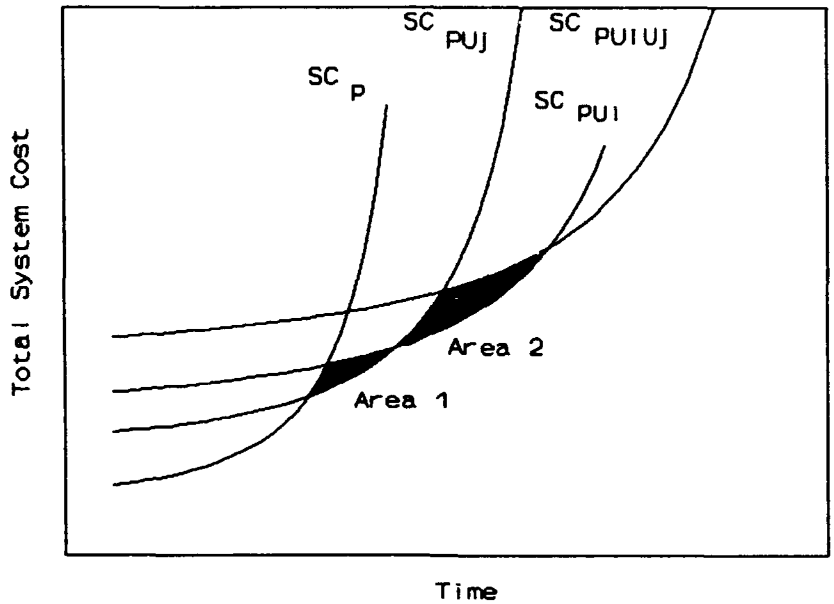

Figure 36 Illustration of Case Three

some decrease in Area 1, which tends to preserve the sequence. The shift in SC_{oPUj} has the opposite effect on the areas as SC_{oPUi}, favoring a swapping in the sequence.

In summary, interdependence causes a non-uniform, downward shift in the system cost curves for all combinations. While, the system cost curves shift due to interdependence, none of the basic properties are changed. Shifts in some combinations will be greater than others. In general, the shifts may cause a swap in the expansion sequence. The potential swapping is due to a change in the areas representing the difference in total costs for two competing combinations.

Creating Mutually Independent Project Clusters

In Chapter 3, the possible decomposition of the project set was discussed as a method of prescreening the solution space in hopes of reducing the overall complexity of interdependent project sequencing and scheduling. Perhaps more importantly, a decomposition methodology is a useful result for various types of analysis on the waterways. Decomposition involves subdividing the set of projects into mutually independent clusters of projects. Clusters are those project subsets where each project 1) interacts with

at least one other project in the subset and 2) is independent of all projects in other subsets.

The clustering procedure involves taking a series of locks and determining which subsets of this series have mutually independent elements. Groups of locks that are on different segments of the waterway are assumed mutually independent. However, these groups may be further divided into clusters. This subdivision of a series of locks may be achieved by establishing pairwise comparisons among all projects in the series. Associated with each comparison is a significance test for interdependence. The quantity for such a test is simply the interdependence coefficient for a two lock system, $(S/I)_{12}$

$$(S/I)_{12} = \alpha \max(\rho_1,\rho_2)^{\beta} (U_{12})^{\gamma} (D_{12})^{\delta}. \qquad \text{Eq. 5.13}$$

A simple network representation is one way to use Eq. 5.13 in establishing possible independent clusters among a series of locks. Let nodes represent locks and arcs represent the existence of an interdependent relation between two locks. If, according to the coefficient, two locks are shown to be interdependent, an arc connecting the two locks, is placed. A significance level, representing the minimum S/I that is necessary to consider the two locks independent is specified. In other words, although two projects are not absolutely independent unless S/I=1.0, they may be considered independent for practical purposes if S/I is slightly less than 1.0. It is the decision of the analyst to suggest a tolerable level of interdependence, e.g. 0.03, based on the desired level of analytic precision. The completed network may then be examined for completely detached clusters.

An illustration of how such an interdependence network may be used to determine mutually exclusive clusters is provided by Figure 37. In this example, a series of five projects is considered for subdivision. Given the distance between locks and utilization, S/I may be computed for any pair of the five locks. If a maximum interdependence of .03 is specified, then any pair of locks having an S/I less than .97 is connected by an arc. For example, S/I for Locks 3 and 4 in the figure is .89. Therefore, an arc is constructed between these two locks (nodes). On the other hand, S/I for Locks 2 and 3 is greater than .97 and arc (2,3) is not included in the network. After computing S/I for all possible pairs, detachment in the resulting network yield the possible clusters. Here, Locks 1 and 2 are completely detached from Locks 3, 4, and 5 forming two mutually independent clusters.

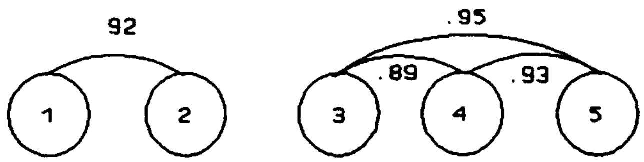

Figure 37 Illustration of Interdependence Network

To construct the network based on a series of n locks, the number of pairwise comparisons equal to that of Eq. 5.14 is necessary. The comparisons correspond to the number of possible links in the interdependence network.

$$\text{Comparisons} = \sum_{i=1}^{n-1} i \qquad \text{Eq. 5.14}$$

All the clusters formed in this manner are considered completely independent from each other with respect to delays. Therefore, the evaluation functions derived in Chapter 4 may be computed independently for each cluster. However, if a budget constraint applies, the clusters are interdependent with respect to the budget. Therefore the computational benefits of clustering are somewhat limited if the same budget constraint applies to different clusters. In Section 5.4, the method of sequencing a single cluster of projects or group of clusters is given.

Sequencing and Scheduling Routine

The methodology for sequencing and scheduling a group of projects is to determine the minimum cost expansion path from plotting the system cost functions for various combinations. Earlier it was shown that interdependence does have some potential effect on the sequence of projects. This effect is due to a downward shift in the curves representing the independent case. Therefore, the sequencing and scheduling routine should account for possible deviations from the independent case.

The method begins with an initial ranking of all projects based upon an independent evaluation. This initial

ranking is then modified iteratively to account for the interdependencies among the projects. The ranking of projects represents a sequence of implementation steps. Beginning with the null alternative, the next project in the sequence is added to the expansion program with each implementation step. At each implementation step, consideration is given to swapping two (or more) of the projects in the sequence. This is done through plotting the total system cost curves.

Total system cost curves are the delay and capital costs for all lock sites. The system cost is computed for each cluster as well as for any independent projects. The costs are then totaled across all clusters and added to the costs of the independent projects to obtain the total system cost.

At each implementation step, four system cost curves are plotted. Each curve represents delay and construction costs for all locks in the system under the implementation of improvements at a subset of the locks. At the first implementation step, the four combinations (project subsets) are C_1) no projects (null), C_2) first ranking project, C_3) second ranking project, and C_4) first and second ranking project, Figure 38. These four curves define two possible paths, 1) null-first-(first & second) or 2) null-second-(first & second). The first path represents no change from the independent ranking, while the second path represents a swap between the first and second ranked projects. The selection between the two paths is based on the relative cumulative costs.

If a lower ranking project is swapped with the project that is ranked one higher, then the lower project is compared with project that is ranked two higher. If a second swap is performed then the project is iteratively compared to the next highest project until no swap is necessary. Following all possible swaps, a new ranking is established. Subsequent implementation steps plot C1) corresponding to current implementation set, C2) corresponding to the addition of the current first ranked among remaining projects, C3).

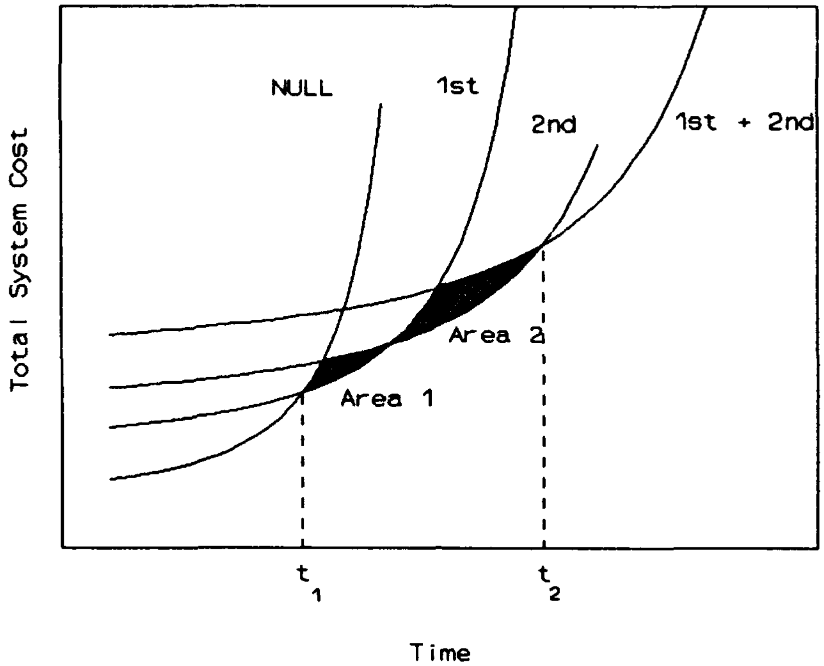

Figure 38 Plot for First Implementation Step

corresponding to the addition of the current second ranked among remaining projects, and C_4) corresponding to the addition of both the current first and second ranked projects. For example, if a swap occurred during the first implementation step, then Figure 39 shows the combinations that would be plotted during the second implementation step. The start times for the projects are determined directly from the plots at each implementation step. For example, in Figure 34, the second ranked project will begin in period t_3. The procedure is described in more detail in the subsections that follow.

Initial Ranking of Projects

The initial sequence is based on a relative evaluation of the projects assuming that they are independent. The evaluation may be made on the basis of the BCR. The benefits of improvement are a reduction in delay associated with the increased capacity, while the costs are the capital

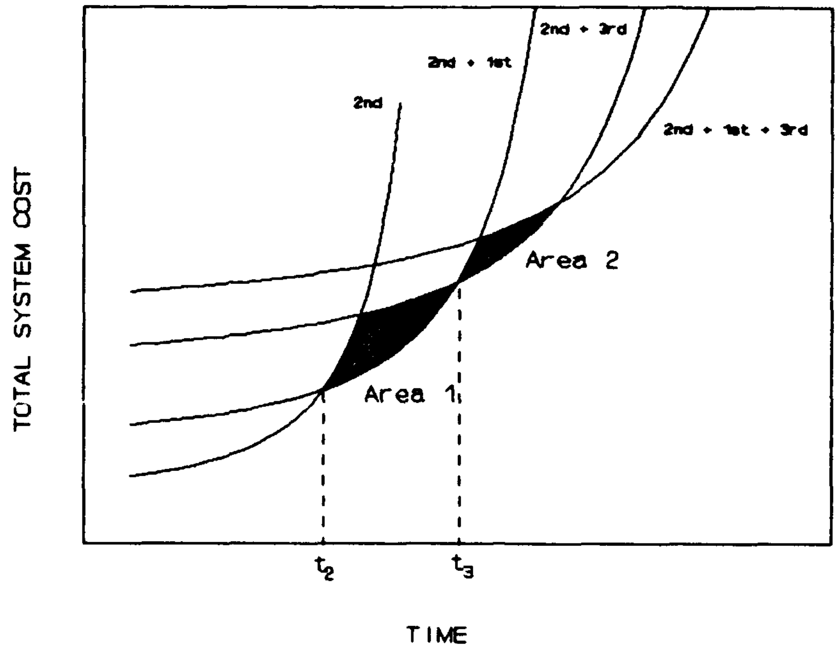

Figure 39 Plot for Second Implementation Step

cost of construction. The BCR of a project i, that is independent from all others, may be written as

$$BCR_i = \sum_{t=0}^{h} ((I_o(t) - I_1(t))\ \lambda(t)_i\ (O_W(t))\ (1+r/2)^{-t})/K_i \qquad \text{Eq. 5.15}$$

where $\quad I(t) = \lambda(t)_i^a\ (1 - \lambda(t)/\mu)^b\ \sigma^c \leq T$

and all terms are as previously defined. It should be noted that the project index on $\lambda(t)_i$ implies that a constant volume for all locks in the system as the example in Chapter 4, is no longer assumed. Also, the opportunity cost of delay may be project specific and be a general function of time. The constant T refers to a congestion tolerance in hours per tow. Tows will divert to other modes or waterways when delays reach $T + \epsilon$. After computing BCR_i for all projects, the projects are ranked according to decreasing BCR. This is the initial ranking (sequence) of the projects. It should be noted, that any project that has a BCR less than 1.0 should be eliminated from the expansion program at this stage of the analysis. This is because the presence of interdependence will only tend to lower a project's BCR.

A Routine for Modifying the Initial Sequence

The routine described in this section for modifying the initial sequence may be either coded algorithmically or performed interactively through a high-level programming environment. The routine begins with an initial ranking/sequence of projects, described by the n dimensional vector $\mathbf{R}_1$, e.g. $\mathbf{R}_1(2)$=A indicates that project A is second in the initial sequence. Project combinations are represented by a vector **C** of indices referring to a subset of projects in the vector $\mathbf{R}_i$. For example, if $\mathbf{R}_i$=(A,B,C,D), then the combination ABD would be expressed by the vector **C**=(1,2,4). The combination corresponding to the null alternative is denoted by **C**=(0). Finally a scheduling vector **T** is defined as the vector of start times corresponding to the projects in the sequence vector **R**. For example, **T**(3)=20 indicates that the third project in the sequence begins in time Period 20. The final sequence and schedule is represented by the vectors $\mathbf{R}_n$ and $\mathbf{T}_n$, respectively.

The first project in the initial sequence is then tested for a possible swap with the second. A possible swap of the first project with the third project may also be considered. However, the computational requirements of the routine increase with the number of possible swaps considered at each iteration. In the interest of clarity, the description in this section is for consideration of one swap at each step.

The following are the steps for sequencing and scheduling a set of interdependent projects in which two or more are interdependent. The number of iterations in the routine is equal one less than the total number of projects and is indexed by i.

Step 1

Compute the net present value according to Eq. 5.15 for each lock, assuming locks are independent. Rank in descending order. Let the initial sequence vector, $\mathbf{R}_0$, equal this ranking. $\mathbf{T}_0$ is initialized to all zeros. Let i=0. Go to Step 2.

Step 2

If i=0, then plot the interdependent system cost (TSC) curves for combinations $\mathbf{C}_1$=**C**(0), $\mathbf{C}_2$=**C**(1), $\mathbf{C}_3$=**C**(2), $\mathbf{C}_4$=**C**(1,2) versus time. If i $\geq$ 1, then plot the curves for $\mathbf{C}_1$=**C**(1,..,i), $\mathbf{C}_2$=**C**(1,..,i,i+1), $\mathbf{C}_3$=**C**(1,..,i,i+2), $\mathbf{C}_4$=**C**(1,..,i,i+1,i+2). The curves begin at a time corresponding to the availability of revenues equal to the

sum of capital costs of the projects contained in a given combination.

$$B(t) = \sum_{j \in C} K_j /crf \qquad \text{Eq. 5.16}$$

The purpose of the plotting in this step is to locate the values of t for which five intersections may take place. These intersections are, t_1: C_1 and C_2, t_2: C_1 and C_3, t_3: C_2 and C_3, t_4: C_2 and C_4, and t_5: C_3 and C_4. The intersections help define areas for combination comparison such as Areas 1 and 2 in the discussion as interdependence three cases. While these intersections may be determined visually if plotted, they may also be determined numerically without plotting. Numerical procedures for efficiently locating the intersections of convex functions currently exist.

The budget constraint is initially considered in this step of the routine. Revenues for major rehabilitations of lock facilities come primarily from the Inland Waterway Trust Fund and the federal matching share. Unspent funds accumulate according to a specified account interest rate. Because the start times for projects are on a continuous rather than discrete scale, the effect of the budget constraint is to delay the earliest possible start time for each combination. Therefore the times corresponding to the five intersection points, t_1, t_2,...,t_5, will be replaced with t'_1, t'_2,...,t'_5. Because a budget limitation may delay the start of a combination, combination curves that would otherwise intersect, will have no intersection. Therefore, times t'_1, t'_2,...,t'_5 do not correspond to intersections but rather to the adjusted earliest start time for a combination.

Figure 40 illustrates an example of the quantities obtained in this step. First, combination C_1 represents the current subset whose sequence has already been determined in previous steps. Combination C_2 represents the resulting combination if the current sequence is maintained, while C_3 represents the resulting combination if a swapping were performed at this step. Combination C_4 represents the implementation of the following project in the current sequence. In this example, the budget constraint has delayed the earliest start time for combination C_2 to t'_1. Therefore Project **R**(i+2) cannot start at t_1.
Go to Step 3.

Step 3

Evaluate to determine if Project **R**(i+1) should be swapped with **R**(i+2) in the sequence. This corresponds to a comparison between C_2 and C_3. The comparison is based on relevant areas defined by the system cost curves and the intersection points found in Step 2. If a swap is made, then a swap between project **R**(i+2) and **R**(i) is considered by redefining C_2 from C(1...i,i+1) to be C(1...i). If a second swap is made, then an additional swap between **R**(i+2) and **R**(i) is considered by setting C_2 to C(1...i-1). Swaps are iteratively considered until a comparison is made where no swap is necessary.

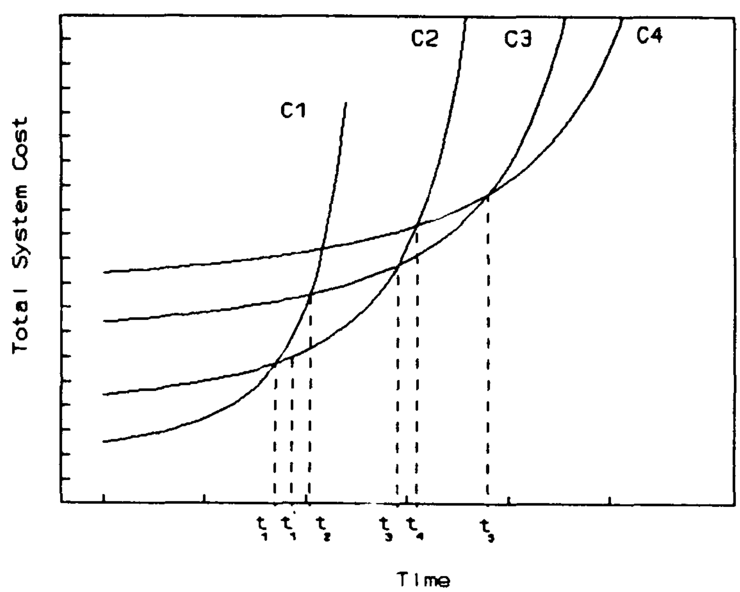

Figure 40 Quantities Obtained in Step Two

In each case, unless one curve lies completely above the other, there will be an area that will favor **R**(i+1) and an area that will favor **R**(i+2). The evaluation is divided into four cases. Cases a and b correspond to Case 1 in Section 5.2, while c and d correspond to Cases 2 and 3 in Section 5.2, respectively. The following tests may be used in making the correct comparisons for evaluation:

a. If the capital costs for combination $\mathbf{C}_2$ are greater than that of $\mathbf{C}_3$ <u>and</u> the minimum capacity in $\mathbf{C}_2$ is less or equal to that of $\mathbf{C}_3$, then $\mathbf{R}_i$(i+1) <u>is</u> swapped with $\mathbf{R}_i$(i+2).

b. If the capital costs for combination $\mathbf{C}_2$ are less than that of $\mathbf{C}_3$ <u>and</u> the minimum capacity in $\mathbf{C}_2$ is greater or equal to that of $\mathbf{C}_3$, then $\mathbf{R}_i$(i+1) is <u>not</u> swapped with $\mathbf{R}_i$(i+2).

However, if a budget limitation delays the earliest start for Combination $\mathbf{C}_2$ to t'_1 then, if $t'_1 > t_2$, the following condition must be tested for a possible swap between $\mathbf{R}_i$(i+1) and $\mathbf{R}_i$(i+2):

$$\int_{t0}^{t'1} TSC(t)_{c1}\,dt + \int_{t'1}^{t5} TSC(t)_{c2}\,dt > \int_{to}^{t2} TSC(t)_{c1}\,dt$$

$$+ \int_{t2}^{t4} TSC(t)_{c3}\,dt + \int_{t4}^{t5} TSC(t)_{c4}\,dt \qquad \text{Eq. 5.17}$$

In addition, if the budget delays the start of Combination $\mathbf{C}_4$ to t'_5 then the third term on the right hand side (RHS) of Eq. 5.17 is omitted and t_5 replaced with t'_5 in the integration limits.

Figure 41 is an illustration of the effects associated with a change in the earliest start time of Combination 2 due to the budget constraint. Without the budget constraint, path $\mathbf{C}_1$-$\mathbf{C}_2$-$\mathbf{C}_4$ starts at 0 with $\mathbf{C}_1$, switches to $\mathbf{C}_2$ at t_1 and switches to $\mathbf{C}_4$ at t_5. However, since funds are not available to begin $\mathbf{C}_2$ at t_1, the system must continue under $\mathbf{C}_1$ until t'_1. Because $t'_1 > t_2$, path $\mathbf{C}_1$-$\mathbf{C}_2$-$\mathbf{C}_4$ is no longer entirely below path $\mathbf{C}_1$-$\mathbf{C}_3$-$\mathbf{C}_4$. Therefore, the test of Eq. 5.17 is necessary to determine which path yields the lower cumulative system costs.

c. If the capital costs for combination $\mathbf{C}_2$ are less than that of $\mathbf{C}_3$ <u>and</u> the minimum capacity in $\mathbf{C}_2$ is less than or equal to that of $\mathbf{C}_3$, then if the condition of Eq. 5.18 holds (Area 1 < Area 2), $\mathbf{R}_i$(i+1) <u>is</u> swapped with $\mathbf{R}_i$(i+2).

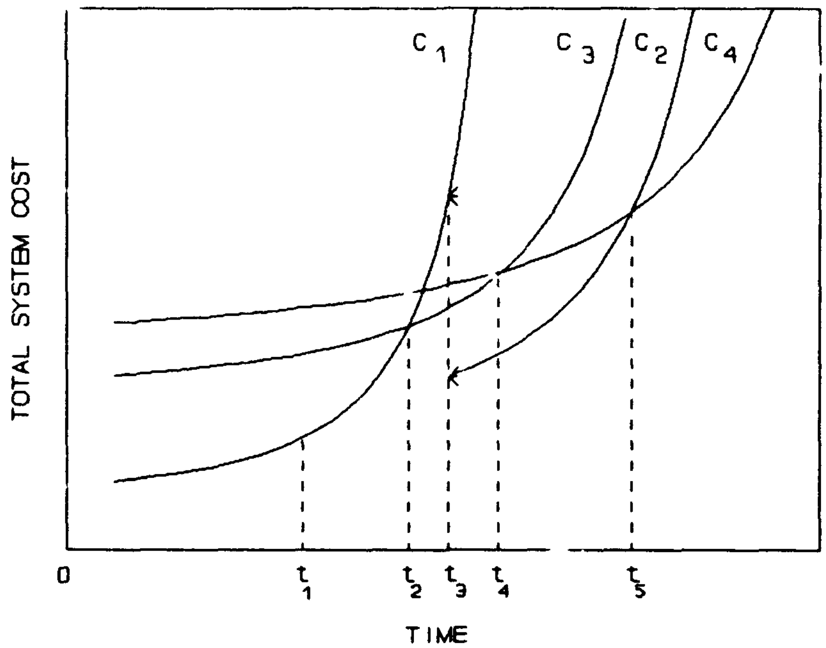

Figure 41 Illustration of Budget Effects (Case 1)

$$\int_{t1}^{t2} (TSC(t)_{c1} - TSC(t)_{c2})dt + \int_{t2}^{t3} (TSC(t)_{c3} - TSC(t)_{c2})dt \quad <$$

$$\int_{t3}^{t4} (TSC(t)_{c2} - TSC(t)_{c3})dt + \int_{t4}^{t5} (TSC(t)_{c4} - TSC(t)_{c3})dt \qquad \text{Eq. 5.18}$$

If the budget constraint alters t_1 and/or t_2, then the LHS of Eq. 5.18 (Area 1) is decreased by an amount given in Eq. 5.19 and increased by an amount given in Eq. 5.20.

$$\int_{t1}^{t'1} (TSC(t)_{c1} - TSC(t)_{c2})dt \qquad \text{Eq. 5.19}$$

$$\int_{t2}^{t'2} (TSC(t)_{c1} - TSC(t)_{c3})dt \qquad \text{Eq. 5.20}$$

Figure 42 is an illustration of the effects of the budget constraint if the earliest start time of C_3 is delayed from t_2 to t'_2. Here, path C_1-C_3-C_4 follows C_1 for an additional period of time (t'_2-t_2) yielding a higher cumulative cost than the same path without the budget constraint. This causes an increase in the size of Area 1.

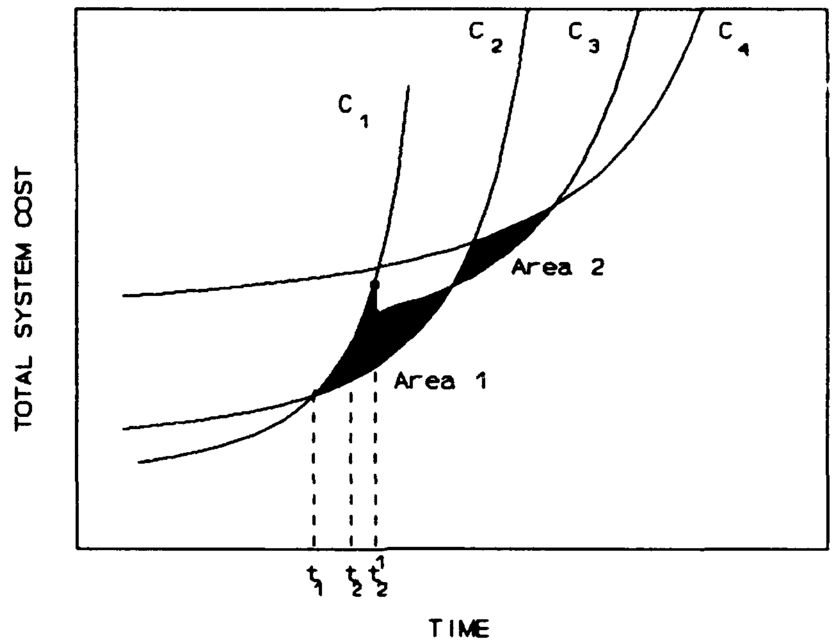

Figure 42 Illustration of Budget Effects (Case 2)

d. If the capital costs for combination C_2 are greater than that of C_3 <u>and</u> the minimum capacity in C_2 is greater or equal to that of C_3, then if the condition of Eq. 5.19 holds, $R_i(i+1)$ <u>is</u> swapped with $R_i(i+2)$.

$$\int_{t2}^{t1} (TSC(t)_{c1} - TSC(t)_{c3})dt + \int_{t1}^{t3} (TSC(t)_{c2} - TSC(t)_{c3})dt \quad \langle$$

$$\int_{t3}^{t5} (TSC(t)_{c3} - TSC(t)_{c2})dt + \int_{t5}^{t4} (TSC(t)_{c4} - TSC(t)_{c2})dt \qquad \text{Eq. 5.21}$$

If the budget constraint alters t_1 and/or t_2, then the LHS of Eq. 5.21 (Area 1) is decreased by an amount given in Eq. 5.22 and increased by an amount given in Eq. 5.23.

$$\int_{t1}^{t'1} (TSC(t)_{c1} - TSC(t)_{c3})dt \qquad \text{Eq. 5.22}$$

$$\int_{t2}^{t'2} (TSC(t)_{c1} - TSC(t)_{c2})dt \qquad \text{Eq. 5.23}$$

In general, TSC(t) is not an integrable function. However, as an approximation, the integrals may be replaced with summations and the limits rounded to the nearest integer value of t. Even better approximations are available through the rule of trapezoids or other numerical techniques. If the combination curves are plotted graphically, it should be possible to compare the sizes of Area 1 and Area 2 visually.
Go to Step 4.

Step 4

The sequence vector, $\mathbf{R}_i$ is updated for iteration i+1. If Projects $\mathbf{R}(i+1)$ and $\mathbf{R}(i+2)$ were not swapped in Step 3, then $\mathbf{R}_{i+1} = \mathbf{R}_i$. If the projects were swapped then let

$$\mathbf{R}_{i+1}(i+1) = \mathbf{R}_i(i+2) \qquad \text{Eq. 5.24}$$

and

$$\mathbf{R}_{i+1}(i+2) = \mathbf{R}_i(i+1). \qquad \text{Eq. 5.25}$$

Go to Step 5.

Step 5

The scheduled start time for the next project in the sequence is obtained directly from one of the intersection points found in Step 2. The following rules apply when assigning the start time for the next project in the sequence:

a. if Project $\mathbf{R}(i+1)$ was <u>not</u> swapped with $\mathbf{R}(i+2)$, then $\mathbf{T}(i+1) = t_1$
b. if Project $\mathbf{R}(i+1)$ <u>was</u> swapped with $\mathbf{R}(i+2)$, then $\mathbf{T}(i+1) = t_2$.

If i=n-1, then stop. Current sequence and schedule are final, otherwise increment i and return to Step 2.

Summary of Routine

The flow chart in Figure 43 provides a summary of the sequencing and scheduling routine described in this section.

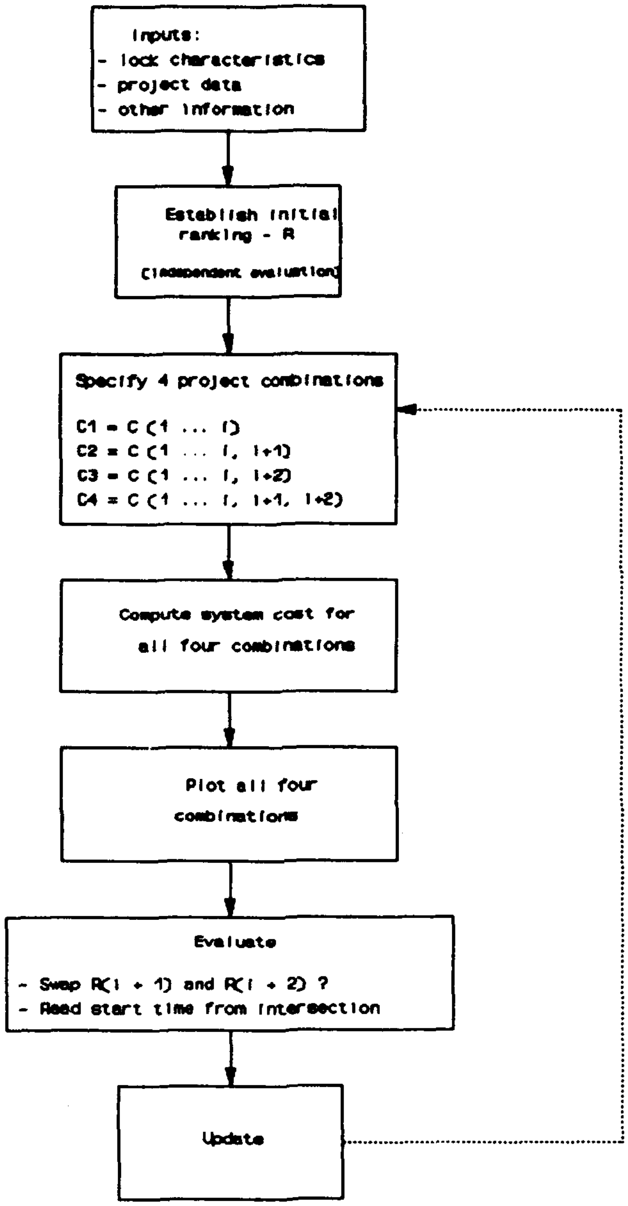

Figure 43 Flow Chart of Sequencing and Scheduling Routine

First, the user specifies the relevant data for the problem. These include 1) lock characteristics such as capacity, volume, distance from the previous lock, and growth rate, 2) project data such as construction costs and capacity improvements, and 3) other information such as planning horizon, interest rates, and congestion tolerance factor. This information is then employed to establish an initial ranking based upon an independent evaluation, described earlier.

At the first iteration, the null alternative and three combinations involving the first two projects in the sequence are specified. Step 2 of the routine describes this specification step for subsequent iterations. Next, the total (delay and construction) system cost is computed for each combination for all time periods. The cost of each of the four combinations is plotted versus time on a single graph. Using the plot, the user determines whether the path $\mathbf{C}_1$-$\mathbf{C}_2$-$\mathbf{C}_4$ or $\mathbf{C}_1$-$\mathbf{C}_3$-$\mathbf{C}_4$ is less costly. If path $\mathbf{C}_1$-$\mathbf{C}_3$-$\mathbf{C}_4$ has the lower cumulative cost, while considering the budget constraint, then projects **R**(i+1) and **R**(i+2) are swapped in the sequence, and the sequence is updated accordingly. An additional swap between **R**(i+2) and **R**(i) is then considered, followed by additional comparisons if swaps are continuously made. Also, if a swap occurred, then the start time for project **R**(i+2) is read from the intersection of $\mathbf{C}_1$ and $\mathbf{C}_3$, else the start time for project **R**(i+1) is read from the intersection of $\mathbf{C}_1$ and $\mathbf{C}_2$. If the end of the project list is not reached, the user specifies the next set of four combinations, and repeats the plotting and evaluation steps.

A Template for Evaluating, Sequencing and Scheduling

The procedure for evaluating, sequencing, and scheduling interdependent lock projects has been programmed as an electronic spreadsheet template. The structure of the template is modular and is shown in Figure 44. Some modules require interaction from the user while others are completely computational. The first module is for problem inputs. Here, the user provides data concerning lock characteristics, proposed project improvements and costs, and other information such as congestion tolerance factor, budget growth rate, and planning horizon.

The inputs are used to directly conduct the independent evaluation for establishing an initial ranking. The inputs are also used to compute the system delay, S_n, for each cluster in each period of the planning horizon. The method for computing S_n is given in detail in Chapter 4. Any project that is not part of an interdependent system is included as an independent project separate from the clusters. Clusters are specified within the template, but are determined outside the template using the method discussed in the section on interdependence.

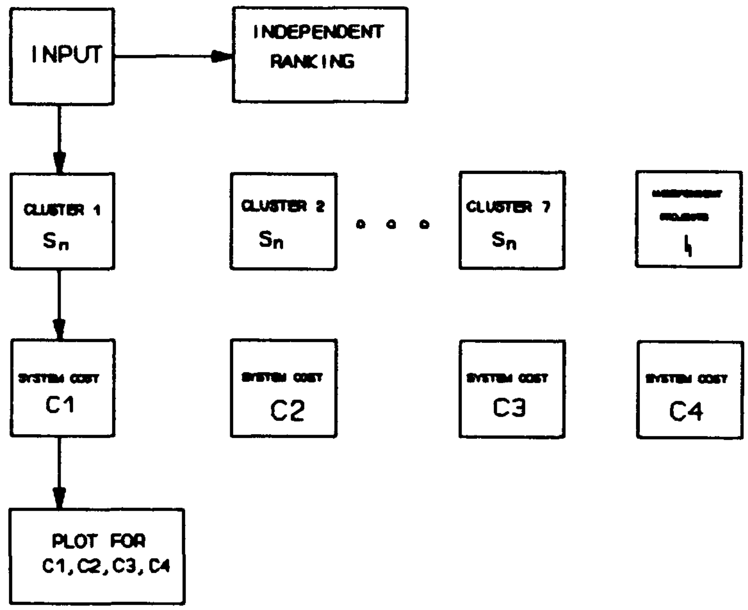

Figure 44 Overview of Template for Lock Investment Planning

The user employs the initial ranking to specify C_1, C_2, C_3, and C_4 for the first iteration in considering a swap in rank between two of the projects. After the four combinations are specified, the template totals the system cost over all clusters and any independent projects for each time period of the planning horizon. The template will not compute the total cost of a combination in a given time period, unless the budget constraint is satisfied. The user may then see an initial plot of the four combinations. He may also work interactively with the graphic utilities of the spreadsheet software to set various plotting ranges and scales. The user may also obtain summation approximations to the relevant areas (Area 1 and Area 2) in order to numerically compare the cumulative costs in determining if a swap among two projects is needed. Plots, interim tables, and results may be easily saved into external files.

Applying the Method to the Inland Navigation System

Problem Summary

The U.S. Army Corps of Engineers is responsible for all operations, maintenance and rehabilitation of the nationwide

system of locks. The Corps has conducted preliminary studies related to rehabilitating numerous locks in the system. Funding for such rehabilitations is at a national level through the Inland Waterway Trust Fund and Federal matching share. Currently, preliminary data are available for proposed capacity expansions at 31 lock and dam sites.

In this section, the method developed in this study is applied to investment planning of these 31 locks subject to the constraints of the Trust Fund and Federal shares. Two possible reconstruction program strategies are being considered by the Corps. The first is to implement all the proposed lock reconstruction projects of a given segment before any are implemented on other segments. The second strategy is to implement projects in the order of economic justification without regard to completing segments. The methodology developed in this dissertation is compatible with both strategies. The first of these implementation strategies is applied in this section.

Because the data are preliminary, no final conclusions concerning the relative merits of the proposed projects may be made. Also, additional expansion projects are expected to be proposed in the near future. However, the application is valuable in illustrating the use of the investment planning method for interdependent locks.

Tables 17 and 18 are an overview of the 31 proposed projects. The sites are spread out over different river segments of the inland navigation system. If the projects are grouped by river segment, they form six groups. The group with the largest number of projects is the upper Mississippi River segment with 11 projects, while Kentucky Lock and Dam is the lone site on the Upper Tennessee River. The table contains information on both existing conditions of the lock at each site, and on the magnitude and estimated cost of the proposed improvement.

Each of the site attributes in Tables 17 and 18 are used in a specific way by the investment planning method. The use of each of these attributes is briefly described.

Distance (D)- This attribute represents the linehaul distance (in miles) to the previous upstream lock. It is used as one of the parameters, in computing S/I.

Table 17 Summary of Inputs for Current Lock Conditions

Project	River Segment	Distance	Current Capacity (Tows/Day)	Current Volume (Tows/Day)
Meldahl	Lower Ohio		30.4	11.2
Markland	Lower Ohio	95	32.2	12.9
McAlpine	Lower Ohio	72	28.1	14.5
Cannelton	Lower Ohio	115	33.1	14.3
Newburgh	Lower Ohio	55	40.6	18.1
Uniontown	Lower Ohio	73	40.8	18.6
Watts Bar	Lower Tenn.		3.9	1.1
Chickamauga	Lower Tenn.	140	4.2	1.9
Nickajack	Lower Tenn.	53	19.2	3.3
Emsworth	Upper Ohio		35.8	15.6
Dashields	Upper Ohio	14	30.8	13.7
Montgomery	Upper Ohio	18	26.9	13.1
Kentucky	Upper Tenn.		14.5	10.1
No. 12	Upper Miss.		13.9	5.5
No. 13	Upper Miss.	34	14.3	5.8
No. 14	Upper Miss.	29	16.7	7.7
No. 15	Upper Miss.	10	18.3	9.1
No. 16	Upper Miss.	25	14.9	7.9
No. 17	Upper Miss.	20	19.3	7.7
No. 18	Upper Miss.	27	14.0	7.7
No. 19	Upper Miss.	46	14.3	7.7
No. 20	Upper Miss.	20	12.9	7.9
No. 21	Upper Miss.	16	14.4	8.2
No. 22	Upper Miss.	15	13.0	8.5
Lockport	Illinois		23.1	8.5
Brandon	Illinois	6	23.0	8.5
Dresden	Illinois	5	20.7	7.7
Marseilles	Illinois	27	16.6	7.4
Starved Rock	Illinois	13	19.9	7.7
Peoria	Illinois	74	18.2	8.5
Lagrange	Illinois	77	15.3	8.2

Table 18 Summary of Lock Inputs for Investment Planning

Project	Proposed Capacity Increase (Tows/Day)	Growth Rate (%)	Current Average V/C	Construction Costs ($ Mill.)	Oppt'y Cost ($/hr.)
Meldahl	11.6	2.05	0.435	225.0	300
Markland	12.2	2.05	0.470	213.4	300
McAlpine	11.8	2.05	0.607	210.0	300
Cannelton	11.1	2.05	0.506	213.4	300
Newburgh	12.9	2.05	0.525	370.7	300
Uniontown	11.8	2.05	0.538	217.3	300
Watts Bar	24.5	1.85	0.327	247.5	175
Chickamauga	26.1	1.85	0.537	180.0	175
Nickajack	35.2	1.85	0.201	70.5	175
Emsworth	64.6	2.05	0.513	294.7	300
Dashields	52.9	2.05	0.524	185.5	300
Montgomery	15.7	2.05	0.489	190.0	300
Kentucky	31.4	1.85	0.819	299.0	175
No. 12	27.1	2.40	0.463	300.0	300
No. 13	28.3	2.40	0.472	320.2	300
No. 14	29.6	2.40	0.542	320.2	300
No. 15	34.3	2.40	0.583	400.2	300
No. 16	27.7	2.40	0.627	320.2	300
No. 17	24.3	2.40	0.468	320.2	300
No. 18	24.0	2.40	0.645	320.2	300
No. 19	10.7	2.40	0.634	280.2	300
No. 20	23.2	2.40	0.723	320.2	300
No. 21	23.2	2.40	0.672	320.2	300
No. 22	23.4	2.40	0.767	320.2	300
Lockport	55.9	1.85	0.432	480.2	250
Brandon	54.7	1.85	0.435	320.2	250
Dresden	42.9	1.85	0.437	320.2	250
Marseilles	39.6	1.85	0.524	320.2	250
Star. Rock	37.3	1.85	0.455	320.2	250
Peoria	30.3	1.85	0.549	320.2	250
Lagrange	25.7	1.85	0.631	320.2	250

Current Capacity (μ_0)- This attribute represents the average number of tows/day that may be serviced by the existing lock. This quantity is used to compute the current lock utilization, ρ, as well as relative utilization ratio, U.

Proposed Capacity Increase ($\mu'-\mu_0$)- This attribute represents the magnitude of expansion that is expected to be realized after a proposed project is implemented. It is used to compute the capacity of a lock after the proposed project, and the economic benefits associated with the reduced average delay.

Current Volume (λ)- This attribute represents the average number of tows/day that currently arrive at a particular lock site. It is used to compute average delays for both the independent and interdependent cases. It is also used to compute the delay costs that occur at a lock.

Growth Rate (g)- This attribute represents the average percentage annual growth in the number of tows that arrive at a lock each day. It is used to specify a growth function, λ_t, for each lock. The growth function is used to obtain a value for λ in each time period, and at each lock. The growth rate is estimated based on economic projections of the demand for commodities most associated with given locks.

Opportunity Cost (O_W)- This attribute represents the costs associated with an hour of delay. The sources of the cost are both the delayed arrival of the shipment and the equipment and crews. The opportunity costs will, in general, be different for different locks, but tend to be the same within segments.

Capital Costs (K/crf)- This attribute represents the capital costs of construction for the proposed capacity expansion. It is used to compute the system cost for a series of locks.

Defining Mutually Independent Clusters

Because a budget constraint applies to all of the proposed projects, the computational advantages of clustering are limited. However, it is helpful to illustrate the method of clustering a series of locks. Each group of projects along a river segment may possibly be divided into two or more mutually independent clusters. In Section 5.3, a method of conducting pairwise assessments of lock interdependence is provided based on a specified level.

A network may be constructed where links represent a significant interdependence between two projects. Here, it will be assumed that if the interdependence between two projects is less than 3 percent, considered to be independent. This interdependence level corresponds to S/I < 0.97.

Table 19 is a matrix of S/I for all possible pairs of projects for the 11 locks along the upper Mississippi River (UMR). Each element of the matrix is the S/I for the locks corresponding to the address of the element. If the value of an element is < .97, then the interdependence between the two projects is significant. For example element (4,5) = .96 indicates that Locks 15 and 16 are significantly interdependent. Therefore, an arc between Nodes 15 and 16 in the interdependence network in Figure 45 may be included. On the other hand, element (3,10) = .98 indicates that Locks 14 and 22 may be considered as independent from each other. Therefore, no arc between Nodes 14 and 22 may be considered to be independent.

There are noticeable detachments in the interdependence network for the UMR projects, as shown in Figure 5.13. The detachments suggest that there are mutually independent clusters in this group. First, Locks 12 and 13 are independent from each other and all other locks and therefore may be evaluated as independent projects. Second, Locks 14 and 15 are mutually interdependent but independent from all other projects. Therefore, they form a two-lock cluster. Finally, Locks 16 through 22 have no detachments among them. Therefore they constitute a cluster of 7 locks.

Table 19 Interdependence Matrix for UMR Projects

	12	13	14	15	16	17	18	19	20	21	22
12	1.00										
13	0.98	1.00									
14	0.98	0.98	1.00								
15	0.98	0.98	0.95	1.00							
16	0.98	0.98	0.97	0.96	1.00						
17	0.99	0.98	0.98	0.97	0.96	1.00					
18	0.99	0.98	0.98	0.97	0.97	0.96	1.00				
19	0.98	0.98	0.97	0.97	0.96	0.96	0.94	1.00			
20	0.99	0.99	0.98	0.98	0.98	0.97	0.96	0.90	1.00		
21	0.99	0.99	0.98	0.98	0.98	0.98	0.97	0.93	0.92	1.00	
22	0.99	0.99	0.98	0.98	0.98	0.98	0.97	0.94	0.94	0.94	1.00

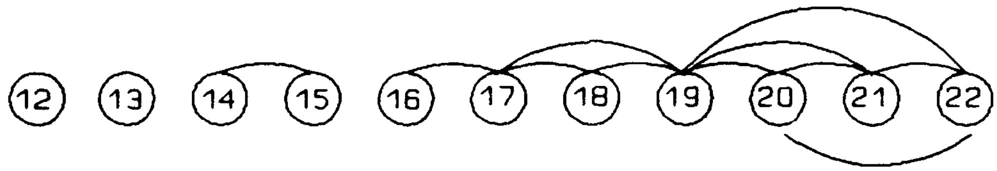

Figure 45 Interdependence Network for UMR Projects

The same routine was applied to the other project groups and mutually independent clusters identified, Table 20. The locks along both the lower and upper Ohio River could not be divided into clusters, while the locks on the Lower Tennessee River are all independent from each other. The Illinois River locks form three clusters with two locks each. These three two-lock clusters are Brandon and Dresden, Marseilles and Starved Rock, and Peoria and Lagrange. The Lockport lock was found to be independent from all others.

Initial Ranking of Projects

The initial ranking of projects is based upon an independent evaluation of all projects according to Eq. 5.15 where the benefit-cost ratio is the measure of effectiveness. With a planning horizon of 50 years, the independent ranking is as shown in Table 21 based on the BCR. Note that not all the projects have a BCR greater than 1.0. Such projects may be eliminated from further steps in the analysis.

Table 20 Resulting Clusters of 31 Locks

1	2	3	4	5	6	7
Meldahl	Emsworth	L&D 14	L&D 16	Brandon	Marseilles	Peoria
Markland	Dashields	L&D 15	L&D 17	Dresdon	Starved Rock	Lagrange
Cannelton	Mongomery		L&D 18			
Newburgh			L&D 19			
Uniontown			L&D 20			
			L&D 21			
			L&D 22			

Table 21 Initial Ranking of 31 Improvement Projects

Rank	Project	BCR[a]
1	McAlpine	6.168
2	Montgomery	5.110
3	L&D 22	4.598
4	Uniontown	4.352
5	Dashields	4.320
6	L&D 20	4.078
7	L&D 21	4.051
8	L&D 19	3.920
9	L&D 18	3.506
10	L&D 16	3.489
11	Emsworth	2.922
12	Newburgh	2.833
13	Cannelton	2.820
14	L&D 15	2.722
15	Kentucky	2.604
16	Markland	2.259
17	L&D 14	1.997
18	Peoria	1.949
19	Meldahl	1.392
20	Lagrange	1.207
21	Marseilles	1.148
22	L&D 17	1.020
23	Starved Rock	0.714
24	L&D 13	0.586
25	L&D 12	0.509
26	Brandon	0.348
27	Dresden	0.230
28	Nickajack	0.084
29	Chickamauga	0.078
30	Watts Barr	0.074
31	Lockport	0.073

[a]/ BCR = Benefit-Cost Ratio

Evaluation, Sequencing, and Scheduling of the Lower Ohio Stem

One of the investment planning strategies of the Corps is to perform reconstruction on all proposed locks for a particular segment before reconstructing locks on other segments. Here, this strategy is employed for sequencing and scheduling projects subject to the Trust Fund budget constraint. A segment given high priority by the Corps is the Lower Ohio River segment. This segment consists of the following locks given in order of their initial ranking:

McAlpine, Uniontown, Newburgh, Cannelton, Markland, and Meldahl In this section, the investment planning methodology is applied this segment of locks.

Table 21 shows that this segment cannot be subdivided into mutually independent clusters. Therefore, the projects are entered into the template as one cluster. Because there are six projects, the procedure will have at least five iterations. At each iteration, the system cost for the six locks will be computed for four combinations of project implementation. Then these combinations are plotted to consider a swap between two projects.

Following the procedure outlined by the flow chart in Figure 39, the input data is provided from Tables 17 and 18, and the initial ranking has been established. The locks are entered into the spreadsheet template in upstream to downstream order: A) Meldahl, B) Markland, C) McAlpine, D) Cannelton, E) Newburgh, and F) Uniontown. Denoting each lock by its letter, the initial ranking vector is $\mathbf{R}_0$=(C,F,E,D,B,A) and the initial scheduling vector is $\mathbf{T}_0$=(0,0,0,0,0,0).

At the first iteration, the total system costs are computed for each time period of the 50 year planning horizon for the following four combinations: $\mathbf{C}_1$=(0), $\mathbf{C}_2$=(C), $\mathbf{C}_3$=(F), and $\mathbf{C}_4$=(C,F). This corresponds to 1) the null alternative, 2) McAlpine only, 3) Uniontown only, and 4) McAlpine and Uniontown. Appendix 3 shows the resulting total system cost under each of the four implementation combinations. Note that there are no entries in the table for $\mathbf{C}_4$ until late periods. This is because it takes the Trust Fund time to accumulate the required $527.3 million.

Figure 46 is a plot of these costs versus time in the relevant regions for evaluation. An evaluation may be made by identifying which path, $\mathbf{C}_1$-$\mathbf{C}_2$-$\mathbf{C}_4$ or $\mathbf{C}_1$-$\mathbf{C}_3$-$\mathbf{C}_4$, is less expensive. From the plot it can be seen that $\mathbf{C}_2$ lies completely below $\mathbf{C}_3$. Therefore, path $\mathbf{C}_1$-$\mathbf{C}_2$-$\mathbf{C}_4$ is preferred, and no swap in the sequence is necessary. The intersection between $\mathbf{C}_1$ and $\mathbf{C}_2$ occurs at a time equal to 8.5 years yielding a start time for Project C of 8.5 years from now. After updating the rank and schedule vectors accordingly, we have: $\mathbf{R}_1$=(C,F,E,D,B,A) and $\mathbf{T}_1$=(8.5,0,0,0,0,0). The index variable, i, is updated from 0 to 1.

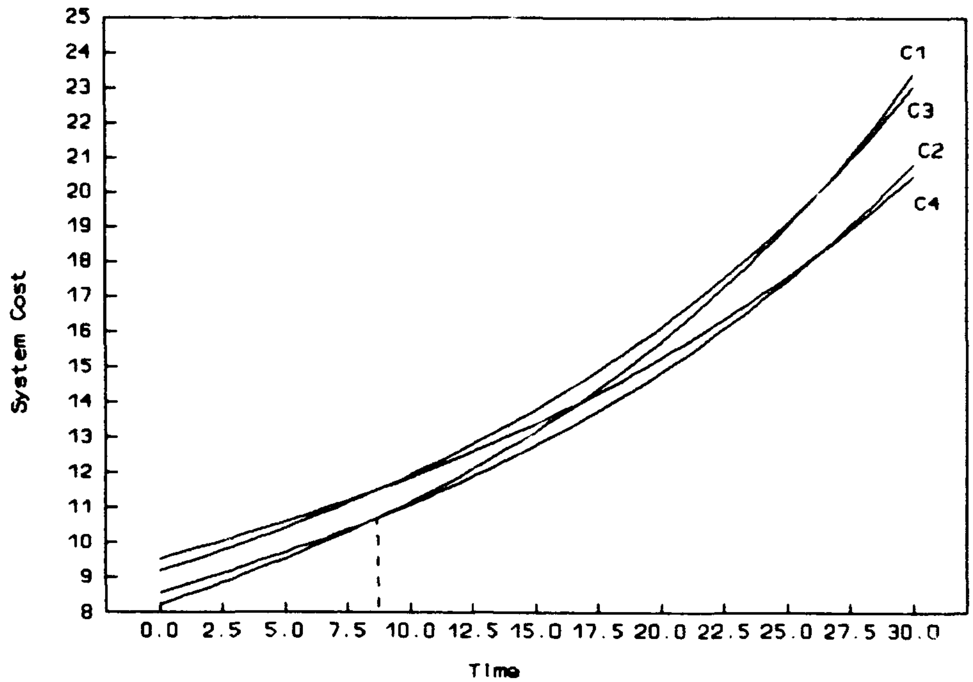

Figure 46 Plot of System Costs for First Iteration

In continuing the routine as outlined in Figure 39, we return to specifying combinations for the beginning of the second iteration. For i=1, the four combination vectors are updated as shown below.

$$\mathbf{C}_1 = \mathbf{C}(1...i) = \mathbf{C}(1) = (C)$$
$$\mathbf{C}_2 = \mathbf{C}(1...i,i+1) = \mathbf{C}(1,2) = (C,F)$$
$$\mathbf{C}_3 = \mathbf{C}(1...i,i+2) = \mathbf{C}(1,3) = (C,E)$$
$$\mathbf{C}_4 = \mathbf{C}(1...i,i+1,i+2) = \mathbf{C}(1,2,3) = (C,E,F)$$

The system cost is computed for the new set of implementation combinations as in the previous iteration. The resulting system costs for the combinations are plotted in Figure 47. Here, the difference in cumulative system costs between the two sequencing paths is quite small. The path $\mathbf{C}_1$-$\mathbf{C}_3$-$\mathbf{C}_4$ has slightly lower cumulative costs than $\mathbf{C}_1$-$\mathbf{C}_2$-$\mathbf{C}_4$ and Project F is swapped with Project E. The intersection between $\mathbf{C}_1$ and $\mathbf{C}_3$ occurs at t=25.6. The updated rank and schedule vectors are $\mathbf{R}_2$=(C,E,F,D,B,A) and $\mathbf{T}_2$=(8.5, 25.6, 0,0,0,0) respectively. The index variable is incremented to 2.

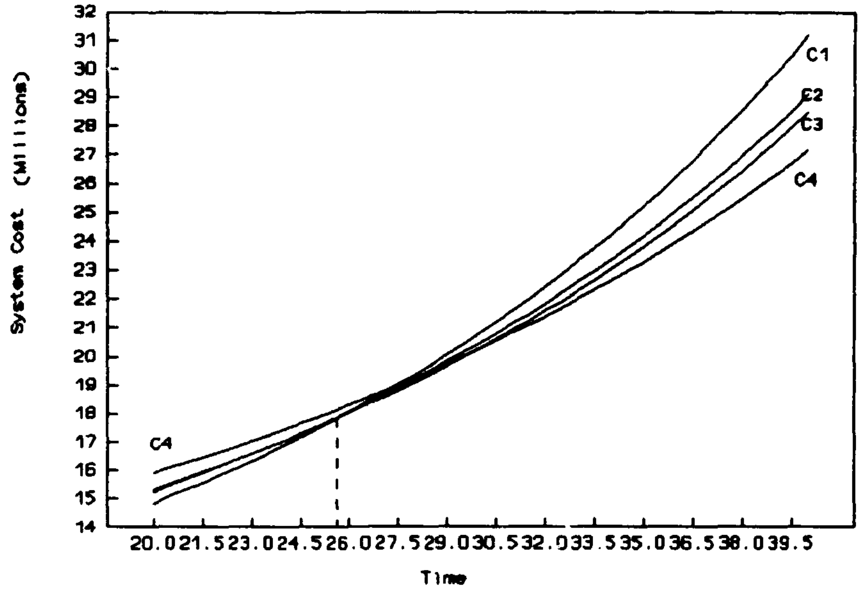

Figure 47 Plot of System Costs for Second Iteration

The following is a summary of the last three iterations of the routine.

<u>Iteration 3</u>

Specifying combinations:

$\mathbf{C}_1 = \mathbf{C}(1...i) = \mathbf{C}(1,2) = (C,E)$
$\mathbf{C}_2 = \mathbf{C}(1...i,i+1) = \mathbf{C}(1,2,3) = (C,E,F)$
$\mathbf{C}_3 = \mathbf{C}(1...i,i+2) = \mathbf{C}(1,2,4) = (C,E,D)$
$\mathbf{C}_4 = \mathbf{C}(1...i,i+1,i+2) = \mathbf{C}(1,2,3,4) =$
(C,E,F,D)

Rank and schedule vectors at the beginning of the iteration:

$\mathbf{R}_2=(C,E,F,D,B,A)$
$\mathbf{T}_2=(8.5,\ 25.6,\ 0,0,0,0)$

Rank and schedule vectors at the end of the iteration:

$\mathbf{R}_3=(C,E,F,D,B,A)$
$\mathbf{T}_3=(8.5,\ 25.6,\ 29.7,\ 0,0,0)$

Iteration 4

Specifying combinations:

C_1 = C(1...i) = C(1,2,3,4) = (C,E,F,D)
C_2 = C(1...i,i+1) = C(1,2,3,4) = (C,E,F,D,B)
C_3 = C(1...i,i+2) = C(1,2,3,5) = (C,E,F,B,A)
C_4 = C(1...i,i+1,i+2) = C(1,2,3,4,5) =
(C,E,F,D,B,A)

Rank and schedule vectors at the beginning of the iteration:

R_3=(C,E,F,D,B,A)
T_3=(8.5, 25.6, 29.7, 0,0,0)

Rank and schedule vectors at the end of the iteration:

R_4=(C,E,F,D,B,A)
T_4=(8.5, 25.6, 29.7, 35.0, 0,0)

At this point, the sequence has been determined, the purpose of the final iteration is only to schedule the final project, Project A.

Iteration 5

Specifying combinations:

C_1 = C(1...i) = C(1,2,3) = (C,E,F,D,B)
C_2 = C(1...i,i+1) = C(1,2,3,4) =
(C,E,F,D,B,A)

Rank and schedule vectors at the beginning of the iteration:

R_4=(C,E,F,D,B,A)
T_4=(8.5, 25.6, 29.7, 35.0, 0,0)

Rank and schedule vectors at the end of the iteration:

R_5=(C,E,F,D,B,A)
T_5=(8.5, 25.6, 29.7, 35.0, 40.5, 52.1)

The final project, Meldahl, is not scheduled to begin until after the planning horizon of 50 years. The budget constraint did not impose any delays in the start times of projects, nor did it alter the sequence of projects. The expansion path for the entire program is shown in Figure 48.

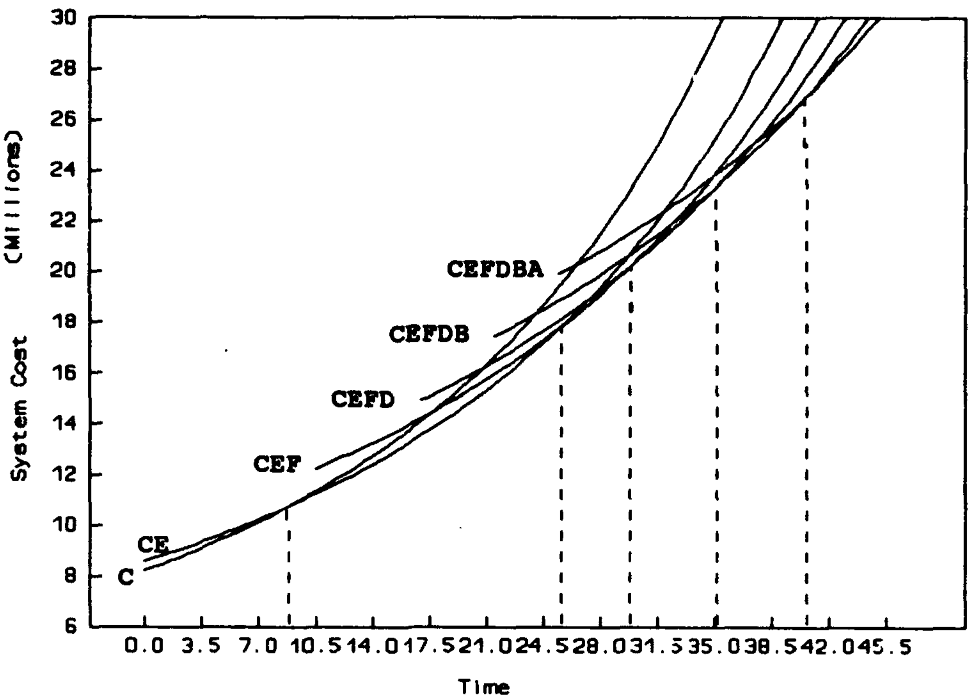

Figure 48 Resulting Expansion Path for Lower Ohio River Segment

Because the final project does not start until after the planning horizon, its implementation is not represented in the figure.

Validation of Sequencing Algorithm

The algorithm presented is not theoretically guaranteed to yield the optimal sequence of projects. Therefore it is necessary to conduct an empirical validation of the algorithm. For validation, two experiments, one with four locks and one with six locks were conducted. In each experiment parameters of lock systems and proposed projects were randomly generated. The algorithm was then applied to each case to obtain a project sequence. Associated with the sequence is a cumulative system cost over the 40 year planning horizon. This sequence is compared to the optimal sequence, i.e. the sequence with the minimum cumulative system cost. The optimal sequence is determined through exhaustive enumeration of possible sequences. There are n! possible sequences, 24 and 750 for four and six lock cases

respectively. There were 30 cases tested for four lock systems and 20 cases tested for six lock systems. The evaluation function used in the experiment is a one-directional metamodel obtained from a recent paper [Dai and Schonfeld 91].

Cases of locks and projects were randomly generated according to a uniform distribution. Ranges of variables were set in such a way as to guarantee a significant amount of interdependence. For example, the distance between locks for four lock systems is fixed at 10 miles and is between 5 and 20 miles for six lock systems. These low distances are not very common for the actual the inland waterway system, but they yield a higher level of interdependence for a more challenging test of the sequencing algorithm. Table 22 shows the range of the randomly generated problem parameters.

Table 22 Range of Problem Parameters for Sequencing Validation

Lower Limit	Parameter	Upper Limit
5	Init. Volume	35
.3	Init. Utilization	.7
1%	Annual Growth Rate	5%
1.5	μ' / μ_0	2
$100	Opportunity Cost	$500
5	Distance	20

The results of the experiments are tabulated in Appendix 5. For each of the two experiments, there is a table providing the inputs for each case and a table providing the outputs for each case. The tables of inputs show: the capacities before and after improvement, the capital cost of improvement for each lock, the initial volume level, growth rate, opportunity cost of delay, and distance between locks. Finally, the resulting BCR for the independent evaluation is given for each project. The output tables contain the sequences based on independent

evaluation, the sequences based on the algorithm, and the optimal sequence obtained from exhaustive enumeration. Also given are the cumulative system cost of the algorithm sequence and the optimal sequence. From these costs an error may be computed for each case.

While the number of cases performed in each experiment is not extraordinarily high, the results suggest that the algorithm is likely to be effective in yielding an efficient project sequence. As the results in Appendix 5 indicate, the four lock experiment had two cases in which the algorithm did not successfully yield the optimal sequence. This is a success rate of 93.3% for the 30 cases. The two suboptimal cases had cumulative costs that were 0.8% and 2.3% higher than optimal. It appears that when the algorithm does not yield an optimal solution, it does yield a reasonable good sub-optimal solution. Similar results were obtained for the six lock experiment. Specifically, the algorithm failed to yield the optimal sequence in one of the 20 six lock cases. This is a success rate of 95%. The error associated for the one suboptimal case was 4.1%.

By examining the cases were the algorithm is in error, ideas for improvements in the algorithm may be obtained. For example, Case 12 of the six lock experiment yielded an incorrect sequence resulting in a cost error of 4.1%. A close examination of this case reveals where in the algorithm the error was made. The algorithm yielded a sequence of 1,4,3,5,6,2 while the optimal sequence is 1,4,3,2,5,6. Applying the algorithm by hand on this case revealed that a swap between Projects 2 and 6 was considered, but the swapping criterion was not satisfied. If we go against the algorithm and consider a swap of Projects 2 and 5, we find that the swapping criterion is satisfied. However, the algorithm on its own does not attempt a swap between 2 and 5 because no swap was performed between 2 and 6.

There may be some adjustments in the algorithm which might eliminate such errors with little cost in computation time. For example, in a given iteration, swaps beyond the first unsuccessful swap may be considered. In other words, if a lower ranked project is not swapped with its predecessor, a swap between it and the next highest project may considered. In order to control the amount of additional computations associated with this change, some maximum percentage cost difference may be specified for the initial comparison as a condition for considering the next highest swap. In applying this change to Case 12, a swap between Projects 2 and 5 would be considered if the cost difference in considering the swap between Projects 2 and 6 is within a specified amount.

Illustrative 30 Lock Case

Practical analysis of inland waterway projects require that numerous improvement projects be considered. It appears from the earlier analysis that clusters of interdependent locks will likely not exceed seven for most segments of the U.S. inland waterways. Therefore, there are significant computational advantages associated with dividing the project set into mutually independent clusters. For this reason, it is helpful to illustrate the sequencing and scheduling procedure for an example involving several clusters. For this example, locks are chosen from among the randomly generated six lock systems from Section 5.7 and are not subject to a budget constraint. The first five cases of six lock systems make up the 30 lock system for this example. These cases are denoted A through E and their optimal sequences are shown in Table 23. The data for Table 23 are extracted directly from Tables 3 and 4 of Appendix 5.

Each six lock system may be thought of as an independent stem in a hypothetical waterway network of 30 locks, Figure 49.

Since the optimal sequence for each six lock system has already been obtained and there is no budget constraint, the optimal sequence and schedule for the 30 locks is straight forward. The reconstruction plan for each stem may be performed independently. That is, the minimum cost expansion path for each stem simultaneously yields the optimal schedule for the whole system. Tables 1 through 6 of Appendix 6 provide the system costs for the optimal sequence of projects for each of the six stems. Each successive column in the Tables of Appendix 6 represents an addition of a project to the expansion path. In each case, the column includes one additional project from the previous column. For example, in Table 1 the first column, with the heading {A4}, represents an implementation set of Project 4 of Stem A, while the second column with the heading {A4,A2} represents the implementation of both Projects A4 and A2.

In each case, the schedule may be obtained by following the combinations that yield the minimum cost in the system. For example, Table 1 shows the combinations that identify the optimal expansion path for System A, which are shown in Table 4 of Appendix 5. Here, this path dictates that Projects 4 and 2 should be implemented immediately, Project 1 should be implemented in Year 17, and Projects 3 and 5 should be implemented in Year 27. Note that the 40 year planning horizon has expired before Project 6 is part of the minimum cost expansion path.

Table 23 Mutually Independent Stems That Make Up the 30 Lock Case

Stem A - from Case 1

Lock	u	u'	K	Vo	g	oc	D	BCR
1	66	115	810	33	2.32	179	10	10.75
2	53	103	745				9.7	12.63
3	73	114	838				6.3	8.09
4	48	89	715				12.4	11.88
5	75	120	974				7.6	6.89
6	54	105	877				8.2	9.78

Optimal Sequence: 421356

Stem B - from Case 2

Lock	u	u'	K	Vo	g	oc	D	BCR
1	34	64	637	17	1.65	273	10	4.74
2	54	83	628				6.9	2.32
3	28	52	412				7.8	11.71
4	35	67	509				15.7	5.42
5	38	66	580				16.9	3.98
6	27	42	261				5.4	8.57

Optimal Sequence: 345162

Stem C - from Case 3

Lock	u	u'	K	Vo	g	oc	D	BCR
1	64	109	957	27	2.63	202	10	5.67
2	63	103	764				10.8	7.08
3	57	98	644				17.6	10.48
4	45	81	727				15.4	10.69
5	67	134	1302				15.2	4.30
6	61	121	1262				16.3	5.05

Optimal Sequence: 423165

Stem D - from Case 4

Lock	u	u'	K	Vo	g	oc	D	BCR
1	47	82	583	31	3.79	179	10	9.81
2	59	92	571				19.0	11.77
3	49	85	697				14.6	8.80
4	79	148	1027				13.5	9.09
5	102	186	1415				10.5	5.13
6	65	115	931				11.3	6.18

Optimal Sequence: 132465

Stem E - from Case 5

Lock	u	u'	K	Vo	g	oc	D	BCR
1	35	57	434	28	1.29	210	10	16.86
2	84	138	1034				15.9	2.83
3	44	85	654				11.2	12.18
4	46	84	722				11.7	9.85
5	44	85	752				16.6	10.55
6	46	91	976				14.2	9.65

Optimal Sequence: 153426

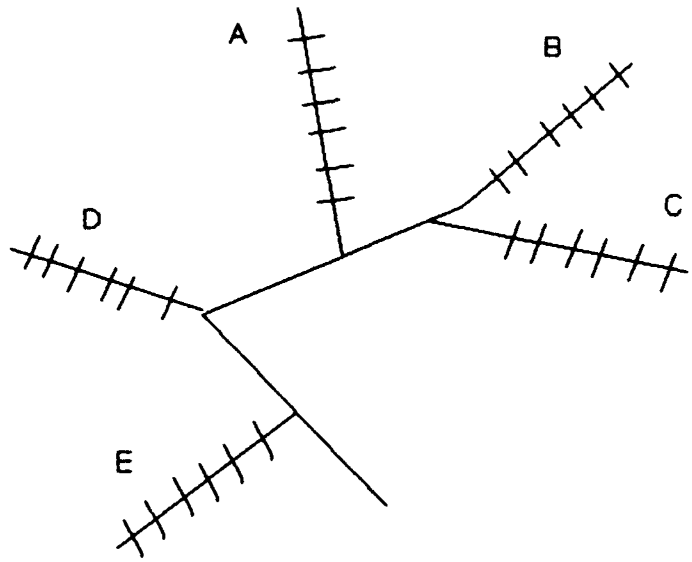

Figure 49 Hypothetical System for 30 Lock Case

At the same time, schedules for Systems B,C,D, and E are derived in a similar manner. Because there is no budget constraint, the schedules for each stem may be integrated simply by superposition. In other words, the schedule for a particular stem is unaffected by the schedules of other stems. The resulting schedule for the thirty lock system is summarized in Table 24. Note that 21 of the 30 projects are implemented before the completion of the 40 year planning horizon.

Summary

Using the slope, intercept, and asymptotic properties of the system cost evaluation functions, it has been shown that, in general, the optimal sequence of projects may be changed due to the effects of interdependence. The establishment of a precedence in the sequence of two projects has been shown to fall in one of three cases. In two of the three cases, the precedence is based on the comparison of two areas defined by five intersection points of the cost functions.

The method for sequencing and scheduling projects begins by establishing an initial sequence based on an independent evaluation. The initial sequence is then

Table 24 Summary of Schedule for Illustrative 30 Lock Case

Year	Project(s) Implemented
0	A4,A2,B5,B4,B3,C4,D1 D3,E1,E5,E3,E4
4	B1
6.5	D2
17	A1
27	A3,A5
28	D4
29	C2,C3
33.5	C1

adjusted to incorporate interdependence. This is done through a heuristic that starts with the highest ranked project and considers a swap (or swaps) in the sequence as each project is added. Conditions for swapping are based upon the precedence conditions for the three cases developed in this chapter, through plotting system cost curves. The start times of projects are determined from the intersections of system cost curves.

As an illustration of the methodology, an investment analysis was performed on the lower Ohio River segment of the inland waterway system. In order to implement the method on this and other problems, the method was programmed as a template on an electronic spreadsheet. The template performs the computationally intensive steps of the methodology as well as provides interactive graphics or summation approximation for potential swapping.

Experiments involving random systems of four and six locks was conducted to provide a validation of the sequencing algorithm. While the number of cases considered was somewhat low, it appears that the algorithm is promising for yielding the optimal solution or at least a good suboptimal solution.

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APPENDICES

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Tables

Appendix A: Simulation Results for S/I Estimation

U = 1.00
V/C = 0.325
V/C = 0.325

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	0.091	0.088	0.0914	0.0940			
5	Dir 2	0.094	0.091	0.0940	0.0918	0.1854	0.1826	0.9850
	Dir 1	0.091	0.088	0.0914	0.0868			
20	Dir 2	0.094	0.087	0.0940	0.0935	0.1854	0.1777	0.9585
	Dir 1	0.091	0.093	0.0914	0.0942			
30	Dir 2	0.094	0.093	0.0940	0.0864	0.1854	0.1837	0.9906

U = 1.00
V/C = 0.66
V/C = 0.66

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	6.688	6.158	6.6878	5.7651			
5	Dir 2	6.453	6.110	6.4534	5.8241	13.1412	11.9283	0.9077
	Dir 1	6.688	6.367	6.6878	6.4396			
20	Dir 2	6.453	6.263	6.4534	5.9645	13.1412	12.5170	0.9525
	Dir 1	6.688	6.469	6.6878	6.2600			
30	Dir 2	6.453	6.165	6.4534	6.1820	13.1412	12.5380	0.9541

U = 1.00
V/C = 0.75
V/C = 0.75

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	16.789	14.740	16.7890	14.6666			
5	Dir 2	17.731	14.320	17.7314	15.1169	34.5204	29.4217	0.8523
	Dir 1	16.789	16.047	16.7890	15.4623			
20	Dir 2	17.731	15.586	17.7314	14.8272	34.5204	30.9613	0.8969
	Dir 1	16.789	15.695	16.7890	16.4289			
30	Dir 2	17.731	15.417	17.7314	16.4800	34.5204	32.0108	0.9273
	Dir 1	16.789	17.193	16.7890	16.2985			
80	Dir 2	17.731	16.948	17.7314	16.6264	34.5204	33.5331	0.9714

U = 1.00
V/C = 0.89
V/C = 0.89

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	47.184	33.362	47.1840	34.3362			
5	Dir 2	46.856	33.337	46.8564	34.0064	94.0404	67.5210	0.7180
	Dir 1	47.184	38.008	47.1840	37.8245			
20	Dir 2	46.856	37.414	46.8564	41.5621	94.0404	77.4047	0.8231
	Dir 1	47.184	39.477	47.1840	40.0460			
30	Dir 2	46.856	40.721	46.8564	38.9282	94.0404	79.5864	0.8463
	Dir 1	47.184	43.751	47.1840	44.0378			
80	Dir 2	46.856	45.177	46.8564	45.0908	94.0404	89.0280	0.9467

U = .845
V/C = 0.32
V/C = 0.27

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	0.091	0.089	0.0858	0.0810			
5	Dir 2	0.094	0.094	0.0770	0.0822	0.1741	0.1730	0.9938
	Dir 1	0.091	0.088	0.0858	0.0802			
20	Dir 2	0.094	0.095	0.0770	0.0810	0.1741	0.1720	0.9879
	Dir 1	0.091	0.090	0.0858	0.0807			
30	Dir 2	0.094	0.095	0.0770	0.0809	0.1741	0.1731	0.9941

U = .845
V/C = 0.66
V/C = 0.56

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	6.688	6.245	0.8792	0.7490			
5	Dir 2	6.453	6.012	0.9700	0.6774	7.4952	6.8416	0.9128
	Dir 1	6.688	6.303	0.8792	0.7126			
20	Dir 2	6.453	6.374	0.9700	0.7774	7.4952	7.0837	0.9451
	Dir 1	6.688	6.180	0.8792	0.9286			
30	Dir 2	6.453	6.471	0.9700	1.0280	7.4952	7.3033	0.9744

U = .845
V/C = 0.75
V/C = 0.63

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	16.789	15.027	2.1166	1.8655			
5	Dir 2	17.731	15.277	2.1982	1.9750	19.4176	17.0720	0.8792
	Dir 1	16.789	15.636	2.1166	1.9534			
20	Dir 2	17.731	15.549	2.1982	2.0776	19.4176	17.6079	0.9068
	Dir 1	16.789	16.057	2.1166	1.9784			
30	Dir 2	17.731	15.981	2.1982	1.9839	19.4176	18.0001	0.9270
	Dir 1	16.789	16.949	2.1166	2.0072			
80	Dir 2	17.731	16.901	2.1982	2.0768	19.4176	18.9671	0.9768

U = .845
V/C = 0.89
V/C = 0.75

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	47.184	36.382	16.7890	13.5074			
5	Dir 2	46.856	37.091	17.7314	12.4361	64.2804	49.7080	0.7733
	Dir 1	47.184	38.389	16.7890	14.9405			
20	Dir 2	46.856	40.884	17.7314	17.7891	64.2804	56.0011	0.8712
	Dir 1	47.184	40.457	16.7890	14.1989			
30	Dir 2	46.856	40.077	17.7314	19.1335	64.2804	56.9332	0.8857
	Dir 1	47.184	47.079	16.7890	13.7174			
80	Dir 2	46.856	43.266	17.7314	18.9318	64.2804	61.4971	0.9567

U = .633
V/C = 0.32
V/C = 0.20

		Lock 1 Mean I	Lock 1 Mean S	Lock 2 Mean I	Lock 2 Mean S	Total I	Total S	S/I
	Dir 1	0.091	0.090	0.0318	0.0310			
5	Dir 2	0.094	0.093	0.0246	0.0269	0.1209	0.1204	0.9958
	Dir 1	0.091	0.091	0.0318	0.0317			
20	Dir 2	0.094	0.098	0.0246	0.0205	0.1209	0.1206	0.9978
	Dir 1	0.091	0.087	0.0318	0.0279			
30	Dir 2	0.094	0.090	0.0246	0.0338	0.1209	0.1194	0.9874

U = .633
V/C = 0.66
V/C = 0.42

		Lock 1 Mean I	Lock 1 Mean S	Lock 2 Mean I	Lock 2 Mean S	Total I	Total S	S/I
	Dir 1	6.688	6.206	0.5478	0.4711			
5	Dir 2	6.453	6.240	0.5312	0.5392	7.1101	6.7283	0.9463
	Dir 1	6.688	6.328	0.5478	0.5133			
20	Dir 2	6.453	6.417	0.5312	0.5137	7.1101	6.8861	0.9685
	Dir 1	6.688	6.476	0.5478	0.5526			
30	Dir 2	6.453	6.410	0.5312	0.5136	7.1101	6.9757	0.9811

U = .633
V/C = 0.75
V/C = 0.475

		Lock 1 Mean I	Lock 1 Mean S	Lock 2 Mean I	Lock 2 Mean S	Total I	Total S	S/I
	Dir 1	16.789	15.199	0.6486	0.6386			
5	Dir 2	17.731	16.316	0.6904	0.6442	17.9297	16.3985	0.9146
	Dir 1	16.789	15.948	0.6486	0.7366			
20	Dir 2	17.731	16.736	0.6904	0.7351	17.9297	17.0780	0.9525
	Dir 1	16.789	17.202	0.6486	0.4838			
30	Dir 2	17.731	16.272	0.6904	0.4855	17.9297	17.2215	0.9605
	Dir 1	16.789	17.489	0.6486	0.0478			
80	Dir 2	17.731	17.678	0.6904	0.0494	17.9297	17.6321	0.9834

U = .369
V/C = 0.32
V/C = 0.12

		Lock 1 Mean I	Lock 1 Mean S	Lock 2 Mean I	Lock 2 Mean S	Total I	Total S	S/I
	Dir 1	0.091	0.093	0.0118	0.0081			
5	Dir 2	0.094	0.096	0.0082	0.0076	0.1027	0.1025	0.9978
	Dir 1	0.091	0.095	0.0118	0.0068			
20	Dir 2	0.094	0.096	0.0082	0.0076	0.1027	0.1024	0.9972
	Dir 1	0.091	0.085	0.0118	0.0125			
30	Dir 2	0.094	0.091	0.0082	0.0127	0.1027	0.1004	0.9779

U = .369
V/C = 0.66
V/C = 0.24

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	0.091	0.089	0.0118	0.0107			
5	Dir 2	0.094	0.094	0.0082	0.0113	0.1027	0.0998	0.9719
	Dir 1	0.091	0.087	0.0118	0.0096			
20	Dir 2	0.094	0.093	0.0082	0.0106	0.1027	0.1014	0.9870
	Dir 1	0.091	0.093	0.0118	0.0088			
30	Dir 2	0.094	0.096	0.0082	0.0092	0.1027	0.1017	0.9901

U = .369
V/C = 0.75
V/C = 0.28

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	16.789	16.676	0.0858	0.1744			
5	Dir 2	17.731	15.989	0.0770	0.1694	17.3416	16.5040	0.9517
	Dir 1	16.789	16.401	0.0858	0.1499			
20	Dir 2	17.731	17.033	0.0770	0.1423	17.3416	16.8630	0.9724
	Dir 1	16.789	15.873	0.0858	0.3945			
30	Dir 2	17.731	16.668	0.0770	0.4020	17.3416	16.6687	0.9612
	Dir 1	16.789	16.629	0.0858	0.0642			
80	Dir 2	17.731	17.596	0.0770	0.0681	17.3416	17.1786	0.9906

U = .369
V/C = 0.89
V/C = 0.33

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	47.184	40.944	0.0914	0.6010			
5	Dir 2	46.856	41.559	0.0940	0.5464	47.1129	41.7279	0.8857
	Dir 1	47.184	42.602	0.0914	0.8159			
20	Dir 2	46.856	43.259	0.0940	0.8124	47.1129	43.5512	0.9244
	Dir 1	47.184	44.204	0.0914	0.4395			
30	Dir 2	46.856	44.155	0.0940	0.4380	47.1129	44.3568	0.9415
	Dir 1	47.184	44.709	0.0914	0.4645			
80	Dir 2	46.856	44.178	0.0940	0.4570	47.1129	44.9222	0.9535

U = .053
V/C = 0.32
V/C = 0.017

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	0.091	0.089	0.0001	0.0034			
5	Dir 2	0.094	0.089	0.0001	0.0033	0.0928	0.0926	0.9980
	Dir 1	0.091	0.089	0.0001	0.0001			
20	Dir 2	0.094	0.095	0.0001	0.0001	0.0928	0.0920	0.9914
	Dir 1	0.091	0.091	0.0001	0.0016			
30	Dir 2	0.094	0.093	0.0001	0.0017	0.0928	0.0934	1.0063

U = .053
V/C = 0.66
V/C = 0.035

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	6.688	6.426	0.0002	0.1613			
5	Dir 2	6.453	6.179	0.0002	0.1702	6.5708	6.4683	0.9844
	Dir 1	6.688	6.287	0.0002	0.1328			
20	Dir 2	6.453	6.568	0.0002	0.1330	6.5708	6.5603	0.9984
	Dir 1	6.688	6.271	0.0002	0.1230			
30	Dir 2	6.453	6.596	0.0002	0.1329	6.5708	6.5616	0.9986

U = .053
V/C = 0.75
V/C = 0.039

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	16.789	17.594	0.0010	0.4137			
5	Dir 2	17.731	16.868	0.0012	0.1929	17.2613	17.1715	0.9948
	Dir 1	16.789	17.605	0.0010	0.3747			
20	Dir 2	17.731	16.343	0.0012	0.9136	17.2613	16.9868	0.9841
	Dir 1	16.789	16.488	0.0010	0.1291			
30	Dir 2	17.731	16.359	0.0012	1.2645	17.2613	17.0559	0.9881
	Dir 1	16.789	18.175	0.0010	0.2629			
80	Dir 2	17.731	16.989	0.0012	0.4231	17.2613	17.3321	1.0041

U = .053
V/C = 0.89
V/C = 0.047

		Lock 1		Lock 2				
		Mean I	Mean S	Mean I	Mean S	Total I	Total S	S/I
	Dir 1	47.184	47.793	0.0032	0.1312			
5	Dir 2	46.856	44.527	0.0042	0.1286	47.0239	46.2903	0.9844
	Dir 1	47.184	45.167	0.0032	1.6294			
20	Dir 2	46.856	44.327	0.0042	1.5795	47.0239	46.3515	0.9857
	Dir 1	47.184	45.629	0.0032	0.0521			
30	Dir 2	46.856	47.202	0.0042	0.0544	47.0239	46.4690	0.9882
	Dir 1	47.184	48.231	0.0032	0.1975			
80	Dir 2	46.856	45.202	0.0042	0.2100	47.0239	46.9204	0.9978

Appendix B: Simulation Results for Three Lock Systems

Volume level, λ = 30 tows/day
Distance = 20 miles
ρ - utilization
σ^2 - variance of lock service time
I - computed isolated delay
$(S/I)_3$ - interdependence coefficient for the three locks
TW_s - total delay obtained from simulation
TW_m - total delay obtained from the meta model

Lock	ρ	W	σ^2	I	$(S/I)_3$	TM_s	TM_m	%ERR
1	0.890	24.349	1.560	34.25				
2	0.890	22.454	1.561	34.27				
3	0.890	24.443	1.552	33.99	0.751	71.246	76.990	8.06
1	0.890	25.801	1.560	34.25				
2	0.750	2.477	1.113	4.27				
3	0.890	25.330	1.552	33.99	0.770	53.608	55.853	4.19
1	0.890	25.742	1.560	34.24				
2	0.660	0.900	0.784	1.42				
3	0.890	25.276	1.552	33.99	0.781	51.918	54.396	4.77
1	0.890	26.825	1.560	34.24				
2	0.320	0.199	0.213	0.06				
3	0.890	26.098	1.552	33.99	0.823	53.122	56.202	5.80
1	0.750	2.846	1.113	4.27				
2	0.890	23.750	1.561	34.27				
3	0.890	25.205	1.552	33.99	0.770	51.802	55.863	7.84
1	0.750	3.018	1.113	4.27				
2	0.750	2.612	1.113	4.27				
3	0.890	26.497	1.551	33.98	0.802	32.127	34.098	6.13
1	0.750	3.167	1.113	4.27				
2	0.660	0.994	0.784	1.42				
3	0.890	26.042	1.551	33.98	0.813	30.204	32.230	6.71
1	0.750	3.030	1.113	4.27				
2	0.320	0.227	0.213	0.06				
3	0.890	27.050	1.551	33.98	0.844	30.307	32.316	6.63
1	0.750	2.547	1.113	4.27				
2	0.890	31.306	1.561	34.27				
3	0.750	2.961	1.107	4.24	0.790	36.814	35.586	3.33

Lock	ρ	W	σ^2	I	$(S/I)_3$	TM_s	TM_m	%ERR
1	0.750	3.463	1.113	4.27				
2	0.750	2.903	1.113	4.27				
3	0.750	3.171	1.107	4.24	0.820	9.538	10.474	9.82
1	0.750	3.434	1.113	4.27				
2	0.660	0.902	0.784	1.42				
3	0.750	3.214	1.106	4.23	0.830	7.550	8.238	9.11
1	0.750	3.547	1.113	4.27				
2	0.320	0.190	0.213	0.06				
3	0.750	3.218	1.106	4.23	0.862	6.955	7.375	6.05
1	0.660	0.869	0.784	1.42				
2	0.890	25.865	1.561	34.27				
3	0.890	25.595	1.551	33.98	0.781	52.329	54.407	3.97
1	0.660	0.938	0.784	1.42				
2	0.750	2.956	1.113	4.27				
3	0.890	26.622	1.551	33.98	0.813	30.516	32.232	5.62
1	0.660	0.992	0.784	1.42				
2	0.660	1.131	0.784	1.42				
3	0.890	27.017	1.551	33.98	0.828	29.140	30.490	4.63
1	0.660	1.010	0.784	1.42				
2	0.320	0.223	0.213	0.06				
3	0.890	27.730	1.551	33.98	0.856	28.963	30.345	4.77
1	0.660	0.939	0.784	1.42				
2	0.890	33.315	1.561	34.27				
3	0.750	3.204	1.107	4.24	0.800	37.458	33.091	11.66
1	0.660	1.185	0.784	1.42				
2	0.750	3.530	1.113	4.27				
3	0.750	3.318	1.106	4.23	0.830	8.033	8.240	2.58
1	0.660	1.289	0.784	1.42				
2	0.660	0.938	0.784	1.42				
3	0.750	3.303	1.106	4.23	0.846	5.530	5.989	8.31
1	0.660	1.289	0.784	1.42				
2	0.320	0.236	0.213	0.06				
3	0.750	3.368	1.106	4.23	0.874	4.892	4.993	2.06
1	0.660	1.152	0.784	1.42				
2	0.890	29.154	1.561	34.27				
3	0.660	0.971	0.784	1.42	0.813	31.277	34.875	11.51

Lock	ρ	W	σ^2	I	$(S/I)_3$	TM_s	TM_m	%ERR
1	0.660	1.422	0.784	1.42				
2	0.750	2.801	1.113	4.27				
3	0.660	0.993	0.784	1.42	0.842	5.216	5.988	14.80
1	0.660	1.486	0.784	1.42				
2	0.660	0.811	0.784	1.42				
3	0.660	1.025	0.784	1.42	0.857	3.321	3.658	10.12
1	0.660	1.505	0.784	1.42				
2	0.320	0.165	0.213	0.06				
3	0.660	1.169	0.784	1.42	0.885	2.839	2.568	9.54
1	0.320	0.222	0.213	0.06				
2	0.890	26.768	1.561	34.27				
3	0.890	27.338	1.551	33.98	0.823	54.328	56.215	3.47
1	0.320	0.226	0.213	0.06				
2	0.750	2.732	1.113	4.27				
3	0.890	26.044	1.551	33.98	0.844	29.002	32.318	11.43
1	0.320	0.256	0.213	0.06				
2	0.660	1.215	0.784	1.42				
3	0.890	26.814	1.551	33.98	0.856	28.285	30.345	7.28
1	0.320	0.259	0.213	0.06				
2	0.320	0.267	0.213	0.06				
3	0.890	28.284	1.551	33.98	0.890	28.809	30.348	5.34
1	0.320	0.195	0.213	0.06				
2	0.890	33.286	1.561	34.27				
3	0.750	3.442	1.107	4.24	0.843	36.922	33.079	10.41
1	0.320	0.209	0.213	0.06				
2	0.750	3.751	1.113	4.27				
3	0.750	3.461	1.106	4.23	0.862	7.421	7.378	0.59
1	0.320	0.216	0.213	0.06				
2	0.660	0.976	0.784	1.42				
3	0.750	3.448	1.106	4.23	0.874	4.640	4.993	7.60
1	0.320	0.225	0.213	0.06				
2	0.320	0.300	0.213	0.06				
3	0.750	3.848	1.106	4.23	0.913	4.373	3.969	9.23
1	0.320	0.190	0.213	0.06				
2	0.890	31.413	1.561	34.27				
3	0.660	1.026	0.784	1.42	0.856	32.629	34.993	7.25

Lock	ρ	W	σ^2	I	$(S/I)_3$	TM_s	TM_m	%ERR
1	0.320	0.246	0.213	0.06				
2	0.750	2.859	1.113	4.27				
3	0.660	1.202	0.784	1.42	0.874	4.306	5.023	16.64
1	0.320	0.249	0.213	0.06				
2	0.660	0.913	0.784	1.42				
3	0.660	1.210	0.784	1.42	0.885	2.372	2.568	8.29
1	0.320	0.246	0.213	0.06				
2	0.320	0.181	0.213	0.06				
3	0.660	1.215	0.784	1.42	0.922	1.641	1.417	13.70
1	0.320	0.175	0.213	0.06				
2	0.890	27.238	1.561	34.27				
3	0.320	0.247	0.212	0.06	0.905	27.660	34.464	24.60
1	0.320	0.256	0.213	0.06				
2	0.750	2.974	1.113	4.27				
3	0.320	0.250	0.212	0.06	0.919	3.480	4.326	24.30
1	0.320	0.275	0.213	0.06				
2	0.660	1.084	0.784	1.42				
3	0.320	0.200	0.212	0.06	0.928	1.559	1.449	7.04
1	0.320	0.277	0.213	0.06				
2	0.320	0.246	0.213	0.06				
3	0.320	0.202	0.212	0.06	0.956	0.725	0.164	77.36

Appendix C: Second Derivative of System Cost Function

$$\frac{d^2S}{d\lambda^2} =$$

Term 1:

$$a(a-1)\sigma^c\lambda^{a-2}\ (1-\lambda/\mu)^b - a\sigma^c\lambda^{a-1}\ b/\sigma\ (1 - \lambda/\mu)^{b-1}$$

Term 2:

$$- \frac{a\sigma^c\lambda^{a-1}}{\mu}\ b\ (1 - \lambda/\mu)^{b-1} + \frac{\sigma^c\lambda^a}{\mu^2}\ b\ (b - 1)\ (1 - \lambda/\mu)^{b-2}$$

Term 3:

$$- (a + \beta)\ (a + \beta + 1)\ \sigma^c\kappa\lambda^{a+\beta+1}\ (1 - \lambda/\mu)^b$$

$$+ (a + \beta)\sigma^c\kappa\lambda^{a+\beta+1}\ b/\mu\ (1 - \lambda/\mu)^{b-1}$$

Term 4:

$$- \sigma^c\kappa\ (a + \beta)\ \lambda^{a+\beta+1}\ b(1 - \lambda/\mu)^{b-1}$$

$$+ \sigma^c\kappa\lambda^{a+\beta}\ b/\mu\ (b - 1)(1 - \lambda/\mu)^{b-2}$$

Appendix D: System Costs for First Iteration of LOR Segment

B(t)	t	C1	C2	C3	C4
350	0.0	8233151	8589781	9186495	
359	0.5	8353506	8694098	9300334	
368	1.0	8476207	8800310	9416303	
377	1.5	8601315	8908461	9534454	
386	2.0	8728892	9018598	9654841	
396	2.5	8859001	9130769	9777521	
406	3.0	8991710	9245022	9902551	
416	3.5	9127087	9361408	10029991	
426	4.0	9265203	9479978	10159904	
437	4.5	9406130	9600786	10292352	10488186
448	5.0	9549945	9723887	10427402	10602523
459	5.5	9696725	9849339	10565121	10718913
471	6.0	9846552	9977199	10705581	10837405
482	6.5	9999510	10107528	10848854	10958046
495	7.0	10155685	10240389	10995015	11080889
507	7.5	10315167	10375847	11144142	11205986
520	8.0	10478049	10513966	11296316	11333390
533	8.5	10644428	10654817	11451620	11463157
546	9.0	10814403	10798470	11610141	11595345
560	9.5	10988077	10944998	11771968	11730012
574	10.0	11165560	11094478	11937194	11867220
588	10.5	11346960	11246986	12105915	12007031
603	11.0	11532395	11402604	12278230	12149511
618	11.5	11721984	11561416	12454244	12294725
633	12.0	11915850	11723507	12634063	12442743
649	12.5	12114125	11888967	12817798	12593636
665	13.0	12316941	12057889	13005565	12747477
682	13.5	12524439	12230367	13197485	12904342
699	14.0	12736763	12406502	13393680	13064310
716	14.5	12954065	12586395	13594282	13227462
734	15.0	13176500	12770152	13799424	13393880
753	15.5	13404233	12957884	14009247	13563652
771	16.0	13637433	13149704	14223895	13736866
791	16.5	13876277	13345731	14443522	13913615
810	17.0	14120950	13546086	14668284	14093994
831	17.5	14371644	13750897	14898345	14278102
851	18.0	14628558	13960295	15133877	14466042
873	18.5	14891903	14174417	15375059	14657918
894	19.0	15161896	14393404	15622077	14853840
917	19.5	15438765	14617404	15875125	15053923
940	20.0	15722748	14846570	16134405	15258282
963	20.5	16014092	15081060	16400129	15467040
987	21.0	16313059	15321039	16672520	15680323
1012	21.5	16619918	15566680	16951807	15898261
1037	22.0	16934956	15818159	17238233	16120990
1063	22.5	17258468	16075664	17532051	16348651
1090	23.0	17590767	16339387	17833526	16581389

B(t)	t	C1	C2	C3	C4
1117	23.5	17932179	16609528	18142936	16819356
1145	24.0	18283046	16886298	18460571	17062709
1174	24.5	18643728	17169914	18786738	17311611
1203	25.0	19014602	17460604	19121755	17566232
1233	25.5	19396063	17758605	19465959	17826748
1264	26.0	19788527	18064162	19819704	18093343
1295	26.5	20192432	18377535	20183361	18366206
1328	27.0	20608239	18698992	20557320	18645537
1361	27.5	21036394	19028814	20941957	18931542
1395	28.0	21477415	19367294	21337713	19224434
1430	28.5	21931864	19714739	21745066	19524439
1466	29.0	22400306	20071469	22164497	19831790
1502	29.5	22883341	20437819	22596514	20146728
1540	30.0	23381600	20814140	23041654	20469508
1578	30.5	23895753	21200799	23500483	20800394
1618	31.0	24426505	21598180	23973603	21139661
1658	31.5	24974607	22006687	24461649	21487598
1700	32.0	25540851	22426741	24965296	21844505
1742	32.5	26126079	22858785	25485259	22210696
1786	33.0	26731185	23303284	26022298	22586500
1830	33.5	27357118	23760725	26577221	22972260
1876	34.0	28004888	24231622	27150886	23368336
1923	34.5	28675568	24716513	27744211	23775103
1971	35.0	29370306	25215964	28358170	24192956
2021	35.5	30090322	25730571	28993808	24622308
2071	36.0	30836922	26260962	29652237	25063591
2123	36.5	31611500	26807796	30334650	25517260
2176	37.0	32415550	27371772	31042326	25983790
2230	37.5	33250671	27953623	31776634	26463683
2286	38.0	34118581	28554125	32539047	26957463
2343	38.5	35021124	29174097	33331149	27465684
2402	39.0	35960284	29814403	34154648	27988926
2462	39.5	36938201	30475959	35011384	28527802
2523	40.0	37957180	31159733	35903348	29082955
2586	40.5	39019715	31866750	36832694	29655064
2651	41.0	40128505	32598097	37801759	30244846
2717	41.5	41286474	33354925	38813079	30853056
2785	42.0	42496799	34138458	39869417	31480491
2855	42.5	43762939	34949994	40973784	32127994
2926	43.0	45088662	35790916	42129470	32796457
2999	43.5	46478084	36662691	43340078	33486823
3074	44.0	47935713	37566884	44609562	34200090
3151	44.5	49466492	38505163	45942271	34937316
3230	45.0	51075859	39479308	47343002	35699626
3311	45.5	52769807	40491217	48817054	36488209
3394	46.0	54554959	41542920	50370307	37304334
3478	46.5	56438657	42636591	52009292	38149346
3565	47.0	58429058	43774556	53741295	39024678
3655	47.5	60535255	44959310	55574463	39931858

B(t)	t	C1	C2	C3	C4
3746	48.0	62767422	46193529	57517940	40872513
3840	48.5	65136968	47480091	59582023	41848383
3936	49.0	66355937	48822091	60479063	42861323
4034	49.5	67800005	50222864	61581633	43913321
4135	50.0	69306559	51686003	62725886	45006503

Appendix E: Results of Sequencing Validation

Table E-1 Inputs for Four Lock Systems

Case

1	Lock	u	u'	K	Vo	g	oc	BCR
	1	61	111	965	23	2.00	482	6.95
	2	46	76	503				18.16
	3	36	68	520				24.15
	4	55	85	460				14.24

3	Lock	u	u'	K	Vo	g	oc	BCR
	1	42	80	813	28	1.71	329	16.99
	2	59	103	688				12.18
	3	53	94	688				14.63
	4	55	106	959				10.31

4	Lock	u	u'	K	Vo	g	oc	BCR
	1	58	87	466	26	2.08	181	8.27
	2	59	104	908				4.80
	3	81	124	948				2.81
	4	57	92	609				6.96

6	Lock	u	u'	K	Vo	g	oc	BCR
	1	19	36	334	7	3.44	219	1.78
	2	18	30	185				3.24
	3	15	30	296				4.04
	4	19	35	270				2.31

							oc	
7	Lock	u	u'	K	Vo	g	oc	BCR
	1	35	52	351	16	3.21	161	7.10
	2	35	68	639				4.45
	3	26	51	417				8.22
	4	30	51	472				6.59

8	Lock	u	u'	K	Vo	g	oc	BCR
	1	81	144	1117	30	3.72	148	6.33
	2	74	132	970				7.57
	3	83	129	747				8.40
	4	54	85	474				10.81

9	Lock	u	u'	K	Vo	g	oc	BCR
	1	41	81	871	25	3.01	210	8.99
	2	38	63	367				16.71
	3	45	87	785				10.09
	4	38	59	345				15.85

Case

Case	Lock	u	u'	K	Vo	g	oc	BCR
10	1	58	111	877	26	3.23	334	14.47
	2	39	76	744				15.86
	3	37	72	682				16.41
	4	52	91	670				18.57
11	Lock	u	u'	K	Vo	g	oc	BCR
	1	63	115	965	25	2.21	285	5.42
	2	56	97	844				6.89
	3	75	127	817				5.11
	4	57	112	1030				5.90
12	Lock	u	u'	K	Vo	g	oc	BCR
	1	31	54	376	11	3.35	413	6.39
	2	37	62	419				4.31
	3	26	49	458				8.22
	4	33	64	493				4.69
13	Lock	u	u'	K	Vo	g	oc	BCR
	1	84	126	735	28	3.03	260	7.91
	2	50	80	592				16.12
	3	55	107	1097				10.25
	4	44	83	712				14.46
14	Lock	u	u'	K	Vo	g	oc	BCR
	1	91	145	993	33	1.90	284	7.19
	2	88	140	969				7.51
	3	63	112	837				15.67
	4	104	181	1504				4.54
15	Lock	u	u'	K	Vo	g	oc	BCR
	1	31	59	532	16	1.24	351	4.98
	2	31	51	341				7.30
	3	27	45	339				9.12
	4	44	86	678				2.78
16	Lock	u	u'	K	Vo	g	oc	BCR
	1	45	90	907	22	2.95	108	3.58
	2	35	63	503				6.38
	3	36	68	590				5.68
	4	32	57	512				5.81
17	Lock	u	u'	K	Vo	g	oc	BCR
	1	27	48	374	11	3.26	438	7.94
	2	35	59	415				4.41
	3	33	60	437				4.79
	4	33	61	510				4.17

Case

18	Lock	u	u'	K	Vo	g	oc	BCR
	1	48	85	595	27	3.99	307	18.24
	2	61	117	1045				13.25
	3	64	104	609				20.48
	4	50	86	766				14.30
19	Lock	u	u'	K	Vo	g	oc	BCR
	1	45	73	487	19	3.06	135	4.67
	2	38	66	447				6.98
	3	49	86	654				3.25
	4	38	60	340				8.51
20	Lock	u	u'	K	Vo	g	oc	BCR
	1	56	100	934	34	2.55	335	18.48
	2	54	105	932				19.10
	3	81	125	846				15.13
	4	62	122	1262				15.03
21	Lock	u	u'	K	Vo	g	oc	BCR
	1	43	81	799	24	1.29	194	4.66
	2	60	100	790				2.90
	3	40	70	655				6.69
	4	57	102	759				3.32
22	Lock	u	u'	K	Vo	g	oc	BCR
	1	50	83	579	31	1.07	494	29.88
	2	49	95	942				21.40
	3	47	80	665				31.93
	4	57	106	991				14.57
23	Lock	u	u'	K	Vo	g	oc	BCR
	1	34	62	518	16	3.19	165	5.19
	2	39	78	596				3.53
	3	37	65	566				3.90
	4	40	77	553				3.56
24	Lock	u	u'	K	Vo	g	oc	BCR
	1	80	128	999	32	2.35	401	11.89
	2	83	131	776				14.15
	3	79	148	1175				11.51
	4	89	139	813				12.61
25	Lock	u	u'	K	Vo	g	oc	BCR
	1	40	80	609	17	2.23	127	2.09
	2	30	54	479				4.56
	3	41	81	841				1.45
	4	44	70	397				2.43

Case

26	Lock	u	u'	K	Vo	g	oc	BCR
	1	35	54	361	18	3.42	358	20.55
	2	26	47	423				18.20
	3	41	66	470				14.56
	4	31	61	529				16.52
27	Lock	u	u'	K	Vo	g	oc	BCR
	1	79	137	1039	30	2.07	209	4.77
	2	47	83	720				12.59
	3	56	102	942				9.13
	4	44	73	527				15.99
28	Lock	u	u'	K	Vo	g	oc	BCR
	1	36	66	560	24	2.24	151	8.99
	2	49	82	576				6.27
	3	72	135	1025				2.24
	4	60	111	1044				2.63
29	Lock	u	u'	K	Vo	g	oc	BCR
	1	49	80	509	34	1.26	292	28.41
	2	45	79	636				22.50
	3	49	91	765				20.51
	4	73	144	1338				6.90
30	Lock	u	u'	K	Vo	g	oc	BCR
	1	38	72	689	26	2.42	279	14.77
	2	50	81	487				17.74
	3	40	76	798				12.95
	4	57	96	759				9.13

Table E-2 Outputs for Four Lock Experiment

Case	SEQ INDEP.	SEQ ALG.	SEQ OPT	Cost ALG.	Cost OPT.	Error
1	3,2,4,1	4,2,3,1	4,2,3,1	$2.80x10^9$	$2.80x10^9$	0
2	3,2,4,1	3,2,4,1	3,2,4,1	$4.27x10^9$	$4.29x10^9$	0
3	1,3,2,4	3,1,4,2	3,1,2,4	$6.16x10^9$	$6.13x10^9$	0
4	1,4,2,3	1,4,2,3	1,4,2,3	$2.07x10^9$	$2.07x10^9$	0
5	1,2,3,4	1,2,3,4	2,1,3,4	$2.56x10^9$	$2.56x10^9$	0.8%
6	3,2,4,1	3,2,4,1	3,2,4,1	$1.55x10^9$	$1.55x10^9$	0
7	3,1,4,2	3,4,1,2	3,4,1,2	$2.54x10^9$	$2.54x10^9$	0
8	4,3,2,1	4,2,3,1	4,2,3,1	$2.91x10^9$	$2.91x10^9$	0
9	4,2,3,1	4,3,2,1	4,3,2,1	$7.49x10^9$	$7.49x10^9$	0
10	4,3,2,1	3,2,4,1	3,2,4,1	$8.28x10^9$	$8.28x10^9$	0
11	2,4,1,3	2,1,4,3	2,1,4,3	$2.83x10^9$	$2.83x10^9$	0
12	3,1,4,2	3,1,4,2	3,1,4,2	$2.43x10^9$	$2.43x10^9$	0
13	2,4,3,1	4,2,3,1	4,2,3,1	$4.59x10^9$	$4.59x10^9$	0
14	3,2,1,4	3,2,1,4	3,2,1,4	$2.70x10^9$	$2.70x10^9$	0
15	3,2,1,4	3,2,1,4	3,2,1,4	$2.96x10^9$	$2.96x10^9$	0
16	2,4,3,1	4,2,3,1	4,3,2,1	$3.01x10^9$	$2.94x10^9$	2.3%
17	1,3,2,4	1,3,4,2	1,3,4,2	$2.37x10^9$	$2.37x10^9$	0
18	3,1,4,1	1,4,2,3	1,4,2,3	$6.99x10^9$	$6.99x10^9$	0
19	4,2,1,3	4,2,1,3	4,2,1,3	$1.86x10^9$	$1.86x10^9$	0
20	2,1,3,4	2,1,4,3	2,1,4,3	$1.00x10^{10}$	$1.00x10^{10}$	0
21	3,1,4,2	3,4,1,2	3,4,1,2	$3.38x10^9$	$3.38x10^9$	0
22	3,1,2,4	1,3,4,2	1,3,4,2	$2.83x10^{10}$	$2.83x10^{10}$	0
23	1,3,4,2	1,3,4,2	1,2,4,2	$1.94x10^9$	$1.94x10^9$	0
24	2,4,1,3	2,4,1,3	2,4,1,3	$3.9x10^9$	$3.9x10^9$	0
25	2,4,1,3	4,2,1,3	4,2,1,3	$1.73x10^9$	$1.73x10^9$	0
26	1,2,3,4	2,4,1,3	2,4,1,3	$4.99x10^9$	$4.99x10^9$	0
27	4,2,3,1	4,2,3,1	4,2,3,1	$3.62x10^9$	$3.62x10^9$	0
28	1,2,3,4	1,2,3,4	1,2,3,4	$2.05x10^9$	$2.05x10^9$	0
29	1,2,3,4	2,1,3,4	2,1,3,4	$7.33x10^9$	$7.33x10^9$	0
30	2,1,3,4	1,3,2,4	1,3,2,4	$5.22x10^9$	$5.22x10^9$	0

Table E-3 Inputs for Six Lock Experiment

Case	Lock	u	u'	K	Vo	g	oc	D	BCR
1	1	66	115	810	33	2.32	179	10	10.75
	2	53	103	745					12.63
	3	73	114	838					8.09
	4	48	89	715					11.88
	5	75	120	974					6.89
	6	54	105	877					9.78
2	1	34	64	637	17	1.65	273	10	4.74
	2	54	83	628				6.9	2.32
	3	28	52	412				7.8	11.71
	4	35	67	509				15.7	5.42
	5	38	66	580				16.9	3.98
	6	27	42	261				5.4	8.57
3	1	64	109	957	27	2.63	202	10	5.67
	2	63	103	764				10.8	7.08
	3	57	98	644				17.6	10.48
	4	45	81	727				15.4	10.69
	5	67	134	1302				15.2	4.30
	6	61	121	1262				16.3	5.05
4	1	47	82	583	31	3.79	179	10	9.81
	2	59	92	571				19.0	11.77
	3	49	85	697				14.6	8.80
	4	79	148	1027				13.5	9.09
	5	102	186	1415				10.5	5.13
	6	65	115	931				11.3	6.18

Case	Lock	u	u'	K	Vo	g	oc	D	BCR
5	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	35	57	434	28	1.29	210	10	16.86
	2	84	138	1034				15.9	2.83
	3	44	85	654				11.2	12.18
	4	46	84	722				11.7	9.85
	5	44	85	752				16.6	10.55
	6	46	91	976				14.2	9.65
6	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	63	120	1223	28	3.50	480	10	18.11
	2	81	139	1112					15.38
	3	42	79	721					23.10
	4	43	74	473					31.10
	5	52	102	919					23.23
	6	70	108	647					20.15
7	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	30	54	403	12	3.49	490	10	10.64
	2	19	37	316				14.9	23.15
	3	28	45	286				14.9	16.22
	4	17	32	299				18.2	23.37
	5	23	36	268				6.8	23.22
	6	26	50	399				13.8	21.59
8	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	29	55	551	23	1.40	302	10	17.50
	2	46	81	613				14.5	8.22
	3	52	88	742				10.3	5.67
	4	39	61	330				14.6	19.22
	5	34	67	625				7.2	15.71
	6	72	131	1244				12.1	5.18
9	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	68	112	900	30	3.07	250	10	11.72
	2	48	91	755				17.9	14.38
	3	44	80	731				6.3	13.05
	4	73	129	1170				10.4	8.79
	5	77	145	1292				11.6	7.57
	6	48	84	709				8.5	7.84
10	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	50	83	607	28	3.71	270	10	15.88
	2	43	65	460				17.3	13.49
	3	84	158	1304				12.3	7.56
	4	45	68	436				5.6	15.34
	5	78	149	1155				19.5	9.51
	6	75	128	814				17.8	9.43

Case

11	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	30	48	379	18	3.90	379	10	18.51
	2	27	49	337				9.2	22.94
	3	41	74	698				5.7	12.43
	4	44	85	806				6.7	10.68
	5	31	52	308				7.6	25.69
	6	51	95	977				16.8	22.42

12	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	31	50	389	22	2.93	427	10	24.51
	2	54	108	845				11.6	12.01
	3	48	79	499				11.0	22.40
	4	38	73	639				14.2	21.32
	5	56	99	730				8.9	12.23
	6	50	86	725				7.1	14.79

13	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	32	49	289	21	3.01	360	10	27.49
	2	38	61	363				15.3	26.10
	3	35	65	633				8.6	16.55
	4	33	54	347				19.9	26.42
	5	30	61	648				6.2	15.90
	6	53	82	628				5.1	9.70

14	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	18	32	270	13	2.74	362	10	21.20
	2	37	61	364				19.0	5.24
	3	24	42	304				5.2	15.36
	4	25	48	416				17.6	10.67
	5	27	45	356				18.7	10.40
	6	27	55	550				11.2	10.38

15	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	39	68	622	30	3.47	263	10	9.78
	2	45	71	482				5.5	14.59
	3	46	89	769				14.9	13.70
	4	52	81	605				15.0	14.46
	5	49	92	705				7.8	15.51
	6	86	142	1128				6.9	14.54

16	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	44	86	723	34	2.09	204	10	12.76
	2	71	120	801				8.5	10.52
	3	73	110	636				14.0	11.21
	4	65	105	636				17.0	14.88
	5	59	100	725				12.4	14.14
	6	96	176	1443				6.7	8.22

Case

17	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	53	90	785	34	2.13	396	10	25.16
	2	51	83	517				14.2	35.26
	3	49	83	606				15.7	29.88
	4	62	100	810				9.2	24.63
	5	91	145	828				18.2	14.40
	6	60	106	980				8.7	25.51

18	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	63	112	936	27	2.88	360	10	13.47
	2	40	73	676				16.8	19.11
	3	39	72	671				18.2	18.89
	4	43	68	406				15.6	29.02
	5	79	136	867				5.2	10.09
	6	77	145	1138				5.4	10.88

19	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	53	81	481	22	3.86	281	10	16.26
	2	60	103	678				10.3	11.62
	3	35	60	480				19.5	14.28
	4	51	88	735				12.9	11.79
	5	52	89	566				16.1	15.14
	6	35	62	447				9.7	12.65

20	Lock	u	u'	K	Vo	g	oc	D	BCR
	1	26	41	288	20	3.29	102	10	5.42
	2	31	62	562				6.6	4.98
	3	35	64	517				6.6	5.29
	4	48	75	483				14.2	4.17
	5	54	82	507				19.9	3.10
	6	52	81	635				11.9	3.40

Table E-4 Outputs for Six Lock Experiment

CASE	INDEP SEQ	ALG SEQ	OPT SEQ	ALG COST	OPT COST	ERROR
1	241635	421356	421356	5.17×10^{9}	5.17×10^{9}	0
2	364152	345162	345162	3.73×10^{9}	3.73×10^{9}	0
3	432165	432165	423165	2.08×10^{8}	2.08×10^{8}	0
4	214365	132465	132465	5.87×10^{9}	5.88×10^{9}	0
5	135462	153426	153426	5.31×10^{9}	5.31×10^{9}	0
6	453612	421356	345126	1.24×10^{10}	1.24×10^{10}	0
7	452631	425136	425136	6.22×10^{9}	6.22×10^{9}	0
8	415236	154236	154236	6.18×10^{9}	6.18×10^{9}	0
9	231456	321546	321546	6.31×10^{9}	6.31×10^{9}	0
10	142563	241536	241536	7.95×10^{9}	7.95×10^{9}	0
11	526134	521346	521346	6.71×10^{9}	6.71×10^{9}	0
12	134652	143562	143256	7.38×10^{9}	7.51×10^{9}	4.1%
13	142356	514236	514236	8.94×10^{9}	8.94×10^{9}	0
14	134562	153642	153642	5.00×10^{9}	5.00×10^{9}	0
15	526431	524631	524631	3.22×10^{10}	3.22×10^{10}	0
16	451326	154236	154236	5.23×10^{9}	5.23×10^{9}	0
17	236145	321465	321465	1.12×10^{10}	1.12×10^{10}	0
18	423165	234153	234156	8.60×10^{9}	8.60×10^{9}	0
19	153642	351462	351462	7.04×10^{9}	7.04×10^{9}	0
20	132465	123465	123465	6.47×10^{9}	6.47×10^{9}	0

Appendix F: System Costs for Illustrative 30 Lock Case

Table F-1 Costs of Each Combination for the Expansion Path of Stem A

	{A4}	{A4,A2}	{A4,A2,A1}	{A4,A2,A1 A3}	{A4,A2,A1 A3,A5}	{A4,A2,A1 A3,A5,A6}
0.0	41790264	*41782926*	46449001	54075864	61183103	72145603
0.5	42069911	*41942394*	46537257	54141753	61229303	72191803
1.0	42351200	*42101192*	46623612	54205623	61274413	72236913
1.5	42634088	*42259207*	46707927	54267334	61318358	72280858
2.0	42918530	*42416319*	46790058	54326737	61361059	72323559
2.5	43204476	*42572401*	46869848	54383678	61402433	72364933
3.0	43491872	*42727316*	46947135	54437989	61442391	72404891
3.5	43780659	*42880919*	47021747	54489495	61480841	72443341
4.0	44070774	*43033057*	47093502	54538011	61517685	72480185
4.5	44478265	*43183566*	47162206	54583338	61552819	72515319
5.0	45040492	*43346812*	47227657	54625268	61586133	72548633
5.5	45631067	*43575277*	47340996	54671271	61617510	72580010
6.0	46234266	*43876711*	47482897	54789784	61666538	72629038
6.5	46850442	*44210888*	47686640	54907717	61722742	72685242
7.0	47479965	*44585655*	47915230	55090529	61797420	72759920
7.5	48123217	*44967135*	48155177	55300276	61879051	72841551
8.0	48780594	*45355469*	48442894	55513135	61960422	72922922
8.5	49452510	*45750803*	48735571	55759670	62071997	73034497
9.0	50139394	*46181340*	49033300	56039825	62213612	73176112
9.5	50841693	*46688997*	49336178	56325710	62357266	73319766
10.0	51559872	*47208199*	49644299	56617465	62502987	73465487
10.5	52294416	*47739273*	49957762	56915239	62650803	73613303
11.0	53045831	*48282557*	50276667	57219182	62800743	73763243
11.5	53814644	*48838400*	50656156	57546265	62969649	73932149
12.0	54601407	*49407166*	51093346	57895588	63156491	74118991
12.5	55406695	*49989232*	51540838	58252748	63346727	74309227
13.0	56326723	*50596977*	51998927	58617959	63540429	74502929
13.5	57479536	*51244976*	52467916	58991439	63737667	74700167
14.0	58670496	*51908800*	52948121	59373414	63938514	74901014
14.5	59901402	*52588925*	53439868	59764119	64143045	75105545
15.0	61174177	*53285843*	53943494	60163796	64351336	75313836
15.5	62490870	*54000068*	54459350	60572696	64563465	75525965
16.0	63853679	*54732130*	54987799	60991078	64779513	75742013
16.5	65264956	*55482583*	55529217	61419210	64999562	75962062
17.0	66727229	56252000	*56083995*	61857370	65223695	76186195
17.5	68243213	57040978	*56652538*	62305846	65451999	76414499
18.0	69815835	57850138	*57276131*	62805800	65725424	76687924
18.5	71448251	58680125	*57919401*	63321733	66008254	76970754
19.0	73143875	59531610	*58579412*	63850574	66297190	77259690
19.5	74906403	60405294	*59256690*	64392710	66592381	77554881
20.0	76739848	61301905	*59951782*	64948542	66893980	77856480
20.5	78648574	62222201	*60665255*	65518488	67202146	78164646
21.0	80637340	63166974	*61397700*	66102978	67517042	78479542
21.5	82711347	64137050	*62149733*	66702461	67838834	78801334
22.0	84876291	65133290	*62921991*	67317404	68167695	79130195
22.5	87138433	66156592	*63715140*	67948288	68503802	79466302
23.0	89504669	67207895	*64529874*	68595618	68847338	79809838
23.5	91982617	68288180	*65366913*	69259916	69198491	80160991

Table F-1 Continued

24.0	94580721	69398474	*66227011*	69941725	69557453	80519953
24.5	97308372	70539848	*67110950*	70641610	69924424	80886924
25.0	100176050	71713427	*68019549*	71360159	70299610	81262110
25.5	103195492	72920386	*68953661*			
26.0	106379898	74161956	*69914176*	72855727	71075476	82037976
26.5	109744173	75439431	*70902024*	73634047	71476600	82439100
27.0	113305228	76754165	71918178	74433640	*71886824*	82849324
27.5	117082333	78107582	72963653	75255227	*72306386*	83268886
28.0	121097570	79501175	74039511	76099562	*72735533*	83698033
28.5	125376375	80936516	75146865	76967433	*73174519*	84137019
29.0	129948224	82415258	76286878	77859661	*73623607*	84586107
29.5	134847495	83939140	77460770	78777104	*74083065*	85045565
30.0	140114556	85509994	78669817	79720661	*74553174*	85515674
30.5	145797171	87129754	79915360	80691269	*75034222*	85996722
31.0	151952315	88800458	81198805	81689911	*75526506*	86489006
31.5	158648554	90524258	82521628	82717617	*76030334*	86992834
32.0	165969222	92303430	83885378	83775462	*76546023*	87508523
32.5	174016688	94140380	85291686	84864577	*77073901*	88036401
33.0	182918224	96037659	86742267	85986147	*77614307*	88576807
33.5	192834179	97997967	88238923	87141414	*78167592*	89130092
34.0	204045994	100100543	89795729	88343858	*78746292*	89708792
34.5	216935606	102463648	91432417	89612580	*79368511*	90331011
35.0	231681040	104914864	93122677	90920600	*80006214*	90968714
35.5	248762865	107458686	94868785	92269481	*80659849*	91622349
36.0	268849428	110099923	96673142	93660869	*81329878*	92292378
36.5	292899213	112843726	98538290	95096499	*82016782*	92979282
37.0	302967822	115695622	100466914	96578198	*82721057*	93683557
37.5	306969973	118661550	102461855	98107893	*83443217*	94405717
38.0	311095901	121747904	104526127	99687618	*84183797*	95146297
38.5	315352434	124961572	106662922	101319522	*84943348*	95905848
39.0	319746950	128309996	108875628	103005880	*85722443*	96684943
39.5	324287430	131801226	111167847	104749095	*86521677*	97484177
40.0	328982527	135443987	113543406	106551716	*87341667*	98304167

Note: Numbers in italics represent the minimum cost expansion path

Table F-2 Costs of Each Combination for the Expansion Path of Stem B

	{B3}	{B3,B4}	{B3,B4,B5}	{B3,B4,B5} B1}	{B3,B4,B5} B1,B6}	{B3,B4,B5} B1,B6,B2}
0.0	40129573	40960441	*38816402*	39369501	42632001	48879421
0.5	40376733	41169741	*38958021*	39443505	42706005	48943894
1.0	40626308	41381091	*39101047*	39517999	42780499	49008791
1.5	40878335	41594522	*39245501*	39592986	42855486	49074114
2.0	41132848	41810065	*39391405*	39668470	42930970	49139865
2.5	41389884	42027749	*39538780*	39744454	43006954	49206049
3.0	41649480	42247606	*39687649*	39820941	43083441	49272668
3.5	41911674	42469668	*39838035*	39897935	43160435	49339724
4.0	42176505	42693968	39989961	*39975439*	43237939	49407221
4.5	42444013	42920539	40143453	*40053458*	43315958	49475161
5.0	42714239	43149416	40298533	*40131994*	43394494	49543548
5.5	42987223	43380634	40455228	*40211050*	43473550	49612385
6.0	43263009	43614227	40613563	*40290632*	43553132	49681674
6.5	43541640	43850234	40773565	*40370741*	43633241	49751419
7.0	43823159	44088690	40935260	*40451383*	43713883	49821622
7.5	44107613	44329635	41098676	*40532559*	43795059	49892286
8.0	44395048	44573107	41263843	*40614275*	43876775	49963415
8.5	44685512	44819147	41430787	*40696534*	43959034	50035012
9.0	44979053	45067795	41599541	*40779339*	44041839	50107079
9.5	45275721	45319094	41770133	*40862694*	44125194	50179620
10.0	45575567	45573086	41942596	*40946603*	44209103	50252638
10.5	45878644	45829814	42116961	*41031070*	44293570	50326136
11.0	46185004	46089325	42293262	*41116098*	44378598	50400117
11.5	46494703	46351664	42471532	*41201691*	44464191	50474584
12.0	46807798	46616879	42651805	*41287853*	44550353	50549541
12.5	47124344	46885017	42834118	*41374588*	44637088	50624989
13.0	47444403	47156129	43018506	*41461899*	44724399	50700934
13.5	47768034	47430265	43205008	*41549791*	44812291	50777377
14.0	48095299	47707477	43393661	*41638267*	44900767	50854322
14.5	48426262	47987819	43584506	*41727332*	44989832	50931773
15.0	48760989	48271346	43777582	*41816989*	45079489	51009731
15.5	49099547	48558113	43972933	*41907241*	45169741	51088202
16.0	49442003	48848180	44170599	*41998094*	45260594	51167187
16.5	49788430	49141604	44370626	*42089551*	45352051	51246690
17.0	50138900	49438447	44573059	*42181615*	45444115	51326714
17.5	50493487	49738771	44777945	*42274292*	45536792	51407262
18.0	50852268	50042641	44985332	*42367584*	45630084	51488339
18.5	51215322	50350122	45195268	*42461496*	45723996	51569946
19.0	51582729	50661282	45407805	*42556032*	45818532	51652088
19.5	51954574	50976191	45622996	*42651196*	45913696	51734767
20.0	52330940	51294921	45840894	*42746993*	46009493	51817987
20.5	52711918	51617545	46061554	*42843425*	46105925	51901751
21.0	53097596	51944139	46285035	*42940497*	46202997	51986062
21.5	53488069	52274781	46511395	*43038214*	46300714	52070924
22.0	53883432	52609551	46740694	*43136579*	46399079	52156340
22.5	54283784	52948532	46972997	*43235597*	46498097	52242312
23.0	54689227	53291809	47208367	*43335271*	46597771	52328846
23.5	55099865	53639470	47446872	*43435606*	46698106	52415943
24.0	55515808	53991604	47688580	*43536606*	46799106	52503607
24.5	55937165	54348306	47933562	*43638275*	46900775	52591842
25.0	56364053	54709670	48181893	*43740617*	47003117	52680650
25.5	56796589	55075796	48433649	*43843637*	47106137	52770035

Table F-2 Continued

	{B3}	{B3,B4}	{B3,B4,B5}	{B3,B4,B5} B1}	{B3,B4,B5} B1,B6}	{B3,B4,B5} B1,B6,B2}
26.0	57234896	55446786	48688907	*43947338*	47209838	52860001
26.5	57679100	55822746	48947750	*44051725*	47314225	52950550
27.0	58129331	56203783	49210261	*44156802*	47419302	53041685
27.5	58585724	56590011	49476528	*44262573*	47525073	53133411
28.0	59048417	56981545	49746639	*44369042*	47631542	53225730
28.5	59517554	57378504	50020690	*44476214*	47738714	53318646
29.0	59993284	57781014	50298775	*44584093*	47846593	53412161
29.5	60475760	58189201	50580996	*44692683*	47955183	53506280
30.0	60965141	58603198	50867455	*44801988*	48064488	53601005
30.5	61461590	59023142	51158260	*44912012*	48174512	53696339
31.0	61965279	59449174	51453522	*45022759*	48285259	53792287
31.5	62476382	59881442	51753358	*45134235*	48396735	53888850
32.0	62995083	60320097	52057887	*45246442*	48508942	53986032
32.5	63521570	60765296	52367233	*45359386*	48621886	54083836
33.0	64056039	61217203	52681527	*45473070*	48735570	54182266
33.5	64598693	61675987	53000902	*45587498*	48849998	54281324
34.0	65149743	62141823	53325498	*45702675*	48965175	54381014
34.5	65709407	62614894	53655461	*45818605*	49081105	54481339
35.0	66277912	63095387	53990941	*45935292*	49197792	54582301
35.5	66855495	63583500	54332097	*46052740*	49315240	54683904
36.0	67442400	64079436	54679092	*46170953*	49433453	54786151
36.5	68038882	64583407	55032097	*46289935*	49552435	54889044
37.0	68645205	65095634	55391290	*46409691*	49672191	54992587
37.5	69261646	65616344	55756857	*46530224*	49792724	55096783
38.0	69888490	66145778	56128991	*46651538*	49914038	55201634
38.5	70526037	66684184	56507893	*46773639*	50036139	55307143
39.0	71174598	67231819	56893776	*46896528*	50159028	55413313
39.5	71834496	67788954	57286860	*47020211*	50282711	55520147
40.0	72506072	68355870	57687375	*47144691*	50407191	55627648

Table F-3 Costs of Each Combination for the Expansion Path of Stem C

	{C4	{C4,C2	{C4,C2,C3	{C4,C2,C3 C1}	{C4,C2,C3 C1,C6}	{C4,C2,C3 C1,C6,C5}
0.0	35464222	42177859	45789686	54171329	69946329	79531152
0.5	35740667	42425475	45985020	54318832	70093832	79610747
1.0	36020178	42675816	46182343	54467475	70242475	79690869
1.5	36302782	42928899	46381663	54617248	70392248	79771508
2.0	36588502	43184745	46582989	54768137	70543137	79852656
2.5	36877363	43443371	46786326	54920130	70695130	79934301
3.0	37169388	43704795	46991681	55073210	70848210	80016433
3.5	37464601	43969034	47199057	55227361	71002361	80099040
4.0	37763022	44236103	47408459	55382563	71157563	80182109
4.5	38064674	44506017	47619889	55538797	71313797	80265626
5.0	38369576	44778789	47833347	55696039	71471039	80349577
5.5	38677749	45054431	48048834	55854266	71629266	80433944
6.0	38989209	45332955	48266348	56013449	71788449	80518712
6.5	39303975	45614368	48485885	56173561	71948561	80603861
7.0	39622061	45898679	48707440	56334568	72109568	80689373
7.5	39943484	46185894	48931007	56496438	72271438	80775225
8.0	40268254	46476017	49156575	56659133	72434133	80861395
8.5	40596385	46769050	49384134	56822612	72597612	80947860
9.0	40927884	47064991	49613671	56986834	72761834	81034594
9.5	41262761	47363839	49845169	57151750	72926750	81121568
10.0	41601020	47665588	50078610	57317311	73092311	81208755
10.5	41942664	47970230	50313972	57483463	73258463	81296123
11.0	42287695	48277752	50551231	57650148	73425148	81383638
11.5	42636111	48588141	50790358	57817303	73592303	81471267
12.0	42987907	48901378	51031323	57984861	73759861	81558970
12.5	43343076	49217441	51274090	58152750	73927750	81646708
13.0	43701607	49536303	51518618	58320894	74095894	81734439
13.5	44063484	49857932	51764864	58489208	74264208	81822118
14.0	44428691	50182293	52012779	58657605	74432605	81909695
14.5	44797204	50509344	52262309	58825988	74600988	81997121
15.0	45168996	50839038	52513393	58994256	74769256	82084341
15.5	45544037	51171321	52765965	59162300	74937300	82171298
16.0	45922289	51506132	53019954	59330002	75105002	82257929
16.5	46303710	51843403	53275278	59497236	75272236	82344169
17.0	46688251	52183058	53531851	59663867	75438867	82429949
17.5	47075858	52525013	53789576	59829752	75604752	82515195
18.0	47466469	52869173	54048348	59994735	75769735	82599829
18.5	47860015	53215434	54308052	60158650	75933650	82683767
19.0	48256419	53563680	54568563	60321321	76096321	82766919
19.5	48655594	53913784	54829743	60482555	76257555	82849192
20.0	49057446	54265604	55091442	60642148	76417148	82930483
20.5	49461868	54618985	55353496	60799881	76574881	83010687
21.0	49868746	54973757	55615726	60955518	76730518	83089687
21.5	50277950	55329732	55877936	61108806	76883806	83167362
22.0	50689340	55686704	56139914	61259472	77034472	83243583
22.5	51102762	56044447	56401425	61407225	77182225	83318209
23.0	51525308	56402713	56662215	61551749	77326749	83391092
23.5	52100933	56761229	56922005	61692707	77467707	83462073
24.0	52685566	57235918	57180490	61829733	77604733	83530984
24.5	53279352	57767699	57437337	61962434	77737434	83597641
25.0	53983450	58408283	57692181	62090386	77865386	83661851
25.5	54778177	59137884	58079812	62264522	78039522	83723404

Table F-3 Continued

	{C4	{C4,C2	{C4,C2,C3	{C4,C2,C3 C1}	{C4,C2,C3 C1,C6}	{C4,C2,C3 C1,C6,C5}
26.0	*55816353*	59884260	58569362	62527028	78302028	83782077
26.5	*56892432*	60647846	59147058	62832264	78607264	83863921
27.0	*58048032*	61481374	59836694	63257483	79032483	83970180
27.5	*59359318*	62474400	60595044	63692398	79467398	84075302
28.0	*60715710*	63627899	61400000	64190367	79965367	84232199
28.5	*62119250*	64820807	62228858	64744154	80519154	84433166
29.0	63572106	66054923	*63082519*	65313482	81088482	84637430
29.5	65076576	67332156	*63961928*	65898921	81673921	84845040
30.0	66635104	68654534	*64868080*	66555944	82330944	85110922
30.5	68250285	70024214	*65802014*	67235721	83010721	85385669
31.0	69924884	71443495	*66764826*	67936235	83711235	85666654
31.5	71661847	72914826	*67757667*	68674679	84449679	85970430
32.0	73464316	74440823	*68781747*	69466958	85241958	86312224
32.5	75335647	76024281	*69838340*	70284504	86059504	86662753
33.0	77279433	77668192	*70928789*	71128332	86903332	87022275
33.5	79299516	79375762	72054508	*71999509*	87774509	87391060
34.0	81400022	81150436	73216990	*72899162*	88674162	87769387
34.5	83585378	82995912	74417810	*73828473*	89603473	88157544
35.0	85860349	84916177	75658635	*74788692*	90563692	88555831
35.5	88230066	86915530	76941225	*75781136*	91556136	88964558
36.0	90700068	88998614	78267444	*76807196*	92582196	89384047
36.5	93276343	91170458	79639266	*77868339*	93643339	89814632
37.0	95965375	93436517	81058784	*78966122*	94741122	90256660
37.5	98774201	95802721	82528220	*80102186*	95877186	90710491
38.0	101710474	98275528	84049935	*81278275*	97053275	91176498
38.5	104782532	100861991	85626437	*82496234*	98271234	91655071
39.0	107999485	103569830	87260400	*83758024*	99533024	92146613
39.5	111371308	106407518	88954669	*85065726*	100840726	92651543
40.0	114908950	109384381	90712284	*86421553*	102196553	93170299

Table F-4 Costs of Each Combination for the Expansion Path of Stem D

	{D1	{D1,D3	{D1,D3,D2	{D1,D3,D2 D4}	{D1,D3,D2 D4,D6}	{D1,D3,D2 D4,D6,D5}
0.0	38238836	*37078768*	38800033	49133890	60771390	75956883
0.5	38778197	*37389205*	38997573	49299634	60937134	76103964
1.0	39329882	*37703876*	39196158	49466200	61103700	76252591
1.5	39894334	*38022778*	39395659	49633473	61270973	76402729
2.0	40472025	*38345901*	39595937	49801326	61438826	76554338
2.5	41063462	*38673227*	39796837	49969619	61607119	76707370
3.0	41669188	*39004733*	39998191	50138196	61775696	76861772
3.5	42289787	*39340385*	40199812	50306886	61944386	77017486
4.0	42925890	*39680139*	40401494	50475501	62113001	77174441
4.5	43578177	*40023943*	40603015	50643831	62281331	77332564
5.0	44247390	*40371730*	40804126	50811647	62449147	77491765
5.5	44934336	*40723420*	41004556	50978695	62616195	77651950
6.0	45639895	*41078922*	41204010	51144692	62782192	77813009
6.5	46404342	41438123	*41402159*	51309330	62946830	77974821
7.0	47333813	41800895	*41598645*	51472263	63109763	78137248
7.5	48305953	42167089	*41793075*	51633109	63270609	78300138
8.0	49331805	42564693	*41985014*	51791446	63428946	78468366
8.5	50396333	43047134	*42222519*	51975357	63612857	78650369
9.0	51501994	43554090	*42506619*	52202918	63840418	78834724
9.5	52651510	44071955	*42823064*	52497080	64134580	79036147
10.0	53847909	44649178	*43143372*	52796672	64434172	79239572
10.5	55094574	45317929	*43467402*	53101742	64739242	79444906
11.0	56850590	46072602	*43794989*	53412332	65049832	79652047
11.5	58945827	46884690	*44239526*	53751661	65389161	79884060
12.0	61188302	47724896	*44717785*	54102545	65740045	80123603
12.5	63594872	48594494	*45208833*	54460719	66098219	80366244
13.0	66185242	49494836	*45713048*	54826286	66463786	80611909
13.5	68982600	50427360	*46301332*	55269853	66907353	80931025
14.0	72014452	51393599	*46957144*	55774568	67412068	81306548
14.5	75313695	52395187	*47635573*	56295192	67932692	81693036
15.0	78920040	53433872	*48337569*	56832321	68469821	82090876
15.5	82881912	54511523	*49064128*	57386580	69024080	82500473
16.0	87259027	55630147	*49816303*	57958624	69596124	82922248
16.5	92125942	56791903	*50595199*	58549136	70186636	83356644
17.0	97786863	58208928	*51449185*	59206037	70843537	83851324
17.5	104428453	59949007	*52391741*	59942323	71579823	84419017
18.0	111981719	61786956	*53371473*	60706091	72343591	85007539
18.5	120663982	63730753	*54390150*	61498562	73136062	85617815
19.0	130771334	65789311	*55449645*	62321024	73958524	86250821
19.5	142718601	67972636	*56551941*	63174834	74812334	86907588
20.0	157106558	70292002	*57699143*	64061427	75698927	87589205
20.5	174840907	72760174	*58893483*	64982316	76619816	88296824
21.0	197356451	75391675	*60137336*	65939102	77576602	89031665
21.5	227073908	78203114	*61433222*	66933479	78570979	89795017
22.0	241462451	81213600	*62783827*	67967240	79604740	90588251
22.5	246066333	84445249	*64192009*	69042283	80679783	91412816
23.0	250919530	87923833	*65660819*	70160622	81798122	92270256
23.5	256051702	91679600	*67193511*	71324394	82961894	93162207
24.0	261497999	95748340	*68793562*	72535868	84173368	94090413
24.5	267429694	100302017	*70593949*	73926711	85564211	95185985
25.0	273823411	105318011	*72524574*	75425409	87062909	96376818
25.5	280698962	110816945	*74547679*	76992664	88630164	97622993

Table F-4 Continued

	{D1	{D1,D3	{D1,D3,D2	{D1,D3,D2 D4}	{D1,D3,D2 D4,D6}	{D1,D3,D2 D4,D6,D5}
26.0	288133564	116876924	*76668777*	78632316	90269816	98927690
26.5	296223560	123595254	*78893800*	80348475	91985975	100294320
27.0	305090918	131094945	*81229144*	82145549	93783049	101726552
27.5	314892579	139534079	*83681712*	84028271	95665771	103228330
28.0	325834278	149119626	86258967	*86001726*	97639226	104803908
28.5	338191508	160128430	88968991	*88071392*	99708892	106457874
29.0	352342377	172940069	91820549	*90243168*	101880668	108195189
29.5	368821061	188090327	94823166	*92523426*	104160926	110021222
30.0	388408683	206362081	97987208	*94919054*	106556554	111941793
30.5	412296239	228948249	101323983	*97437512*	109075012	113963225
31.0	442396453	257763662	104845849	*100086891*	111724391	116092398
31.5	481991924	296093227	108566343	*102875984*	114513484	118336811
32.0	492571746	305428580	112500323	*105814365*	117451865	120704658
32.5	499419070	311055664	116664142	*108912480*	120549980	123204905
33.0	506477710	316921376	121075840	*112181746*	123819246	125847390
33.5	513762547	323044002	125755374	*115634675*	127272175	128642933
34.0	521290127	329443853	130724888	*119285007*	130922507	131603456
34.5	529078914	336143574	136009024	*123147868*	134785368	134742138
35.0	537149587	343168486	141635295	*127239957*	138877457	138073586
35.5	545525398	350547015	147634529	*131579758*	143217258	141614030
36.0	554232601	358311196	154041399	*136187790*	147825290	145381567
36.5	563300973	366497279	160895055	*141086910*	152724410	149396438
37.0	572764453	375146468	168239900	*146302658*	157940158	153681363
37.5	582661917	384305829	176126530	*151863680*	163501180	158261939
38.0	593038149	394029402	184612885	*157802230*	169439730	163167116
38.5	603945053	404379584	193765687	*164154771*	175792271	168429784
39.0	615443171	415428867	203662228	*170962716*	182600216	174087472
39.5	627603632	427262034	214392637	*178273325*	189910825	180183220
40.0	640510649	439978973	226062762	*186140813*	197778313	186766648

Table F-5 Costs of Each Combination for the Expansion Path of Stem E

	{E1}	{E1,E5}	{E1,E5,E3}	{E1,E5,E3 E4}	{E1,E5,E3 E4,E2}	{E1,E5,E3 E4,E2,E6}
0.0	97147249	75668698	68194513	*62187004*	72715386	84915386
0.5	97791483	76081821	68484661	*62357568*	72873848	85073848
1.0	98442271	76498901	68777238	*62529204*	73033314	85233314
1.5	99099719	76920000	69072273	*62701919*	73193792	85393792
2.0	99763939	77345178	69369797	*62875719*	73355286	85555286
2.5	100435043	77774500	69669839	*63050611*	73517805	85717805
3.0	101113147	78208030	69972431	*63226602*	73681354	85881354
3.5	101798370	78645836	70277604	*63403700*	73845939	86045939
4.0	102490834	79087986	70585390	*63581911*	74011567	86211567
4.5	103190666	79534551	70895823	*63761242*	74178244	86378244
5.0	103897994	79985604	71208935	*63941700*	74345977	86545977
5.5	104612951	80441218	71524760	*64123292*	74514773	86714773
6.0	105335674	80901470	71843335	*64306026*	74684637	86884637
6.5	106066303	81366438	72164693	*64489908*	74855577	87055577
7.0	106804984	81836203	72488872	*64674947*	75027599	87227599
7.5	107551866	82310849	72815909	*64861148*	75200709	87400709
8.0	108307101	82790460	73145841	*65048519*	75374914	87574914
8.5	109070849	83275125	73478707	*65237068*	75550221	87750221
9.0	109843272	83764934	73814547	*65426802*	75726636	87926636
9.5	110624539	84259980	74153401	*65617728*	75904166	88104166
10.0	111414823	84760359	74495311	*65809854*	76082817	88282817
10.5	112214302	85266169	74840318	*66003186*	76262597	88462597
11.0	113023162	85777514	75188466	*66197734*	76443511	88643511
11.5	113841594	86294498	75539799	*66393503*	76625567	88825567
12.0	114669794	86817230	75894363	*66590502*	76808770	89008770
12.5	115507967	87345821	76252203	*66788738*	76993129	89193129
13.0	116356322	87880388	76613368	*66988219*	77178649	89378649
13.5	117215078	88421049	76977905	*67188952*	77365337	89565337
14.0	118084461	88967929	77345864	*67390945*	77553199	89753199
14.5	118964703	89521154	77717297	*67594206*	77742243	89942243
15.0	119856047	90080857	78092255	*67798742*	77932475	90132475
15.5	120758743	90647175	78470792	*68004561*	78123901	90323901
16.0	121673051	91220249	78852963	*68211672*	78316528	90516528
16.5	122599240	91800225	79238825	*68420081*	78510364	90710364
17.0	123537590	92387255	79628434	*68629797*	78705413	90905413
17.5	124488392	92981496	80021851	*68840827*	78901684	91101684
18.0	125451946	93583112	80419135	*69053179*	79099182	91299182
18.5	126428567	94192273	80820351	*69266862*	79297913	91497913
19.0	127418580	94809153	81225562	*69481883*	79497886	91697886
19.5	128422325	95433935	81634833	*69698249*	79699105	91899105
20.0	129440154	96066810	82048233	*69915971*	79901577	92101577
20.5	130472436	96707975	82465832	*70135054*	80105308	92305308
21.0	131519554	97357635	82887702	*70355507*	80310306	92510306
21.5	132581908	98016004	83313916	*70577339*	80516575	92716575
22.0	133659915	98683305	83744550	*70800557*	80724123	92924123
22.5	134754010	99359770	84179683	*71025169*	80932955	93132955
23.0	135864650	100045642	84619395	*71251183*	81143077	93343077
23.5	136992308	100741173	85063770	*71478609*	81354495	93554495
24.0	138137485	101446627	85512893	*71707452*	81567215	93767215
24.5	139529369	102162280	85966853	*71937723*	81781243	93981243
25.0	141226869	103038733	86425741	*72169429*	81996584	94196584
25.5	143142348	104075128	86889652	*72402577*	82213244	94413244

Table F-5 Continued

	{E1}	{E1,E5}	{E1,E5,E3}	{E1,E5,E3 E4}	{E1,E5,E3 E4,E2}	{E1,E5,E3 E4,E2,E6}
26.0	145102180	105132428	87358681	*72637177*	82431228	94631228
26.5	147107949	106211317	87832932	*72873236*	82650542	94850542
27.0	149161313	107312513	88312506	*73110763*	82871190	95071190
27.5	151264017	108436767	88797511	*73349765*	83093178	95293178
28.0	153417894	109584866	89288060	*73590251*	83316510	95516510
28.5	155807395	110788304	89784266	*73832229*	83541191	95741191
29.0	158348329	112032767	90286248	*74075706*	83767224	95967224
29.5	160958516	113304805	90794132	*74320692*	83994615	96194615
30.0	163640783	114605402	91308044	*74567194*	84223367	96423367
30.5	166398112	115935590	91828116	*74815219*	84453484	96653484
31.0	169233656	117296455	92393767	*75064777*	84684970	96884970
31.5	172150751	118689141	92994788	*75315874*	84917826	97117826
32.0	175152927	120114853	93603888	*75568519*	85152056	97352056
32.5	178243923	121574859	94221252	*75822719*	85387663	97587663
33.0	181427704	123070500	94847072	*76078483*	85624647	97824647
33.5	184708480	124603189	95481546	*76335817*	85863012	98063012
34.0	188090723	126174423	96124882	*76594730*	86102758	98302758
34.5	191579187	127785781	96777293	*76855228*	86343886	98543886
35.0	195178934	129438939	97439003	*77117320*	86586396	98786396
35.5	198895357	131135670	98110243	*77381012*	86830288	99030288
36.0	202734211	132877857	98791255	*77646311*	87075560	99275560
36.5	206701638	134667498	99482291	*77913224*	87322211	99522211
37.0	210804210	136506717	100183612	*78181758*	87570239	99770239
37.5	215048957	138397776	100895491	*78451920*	87819641	100019641
38.0	219443417	140343082	101937724	*78792229*	88070413	100270413
38.5	223995677	142345204	103162530	*79169321*	88424503	100624503
39.0	228714427	144406885	104420989	*79550742*	88787481	100987481
39.5	233609020	146531058	105714587	*79936573*	89154761	101354761
40.0	238689533	148720862	107044901	*80326896*	89526425	101726425

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13. ABSTRACT *(Maximum 200 words)*

The Inland Navigation System is an important source of commodity transportation in the U.S. Lock facilities are a necessary part of the system, but can be a source of tow delays. The expansion and rehabilitation of locks present an interesting problem in capital budgeting. The traffic flows at locks are interdependent, i.e. the delays at one lock are related to the delays at one or more other locks. Interdependence gives rise to difficulties in predicting delays as well as an overwhelming number of permutations of project sequences. In this report, a method of predicitng delays among interdependent locks is developed and used for economic evaluation. The evaluation technique is utilized by a heuristic project sequencing algorithm in obtaining an efficient capital budgeting solution for lock improvement projects.

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